Desalination Water Supply Planning – Optimisation of Environmental Impacts and Costs Using Life Cycle Assessment

by

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A thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the School of Engineering and Information Technology, Murdoch University

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I declare that:

a) This thesis is my own account of my research, except where other sources are acknowledged.
b) The extent to which the work of others has been used is clearly stated in each chapter and certified by my supervisors.
c) The thesis contains as its main content work, which has not been previously submitted for a degree at any other university.

Maedeh Pakzad Shahabi

A note on formatting and style

This PhD thesis includes a number of published research papers. These formatted documents are incorporated into this thesis along with additional texts that has been provided to introduce and link the published work and also additional chapters. It is hoped that the final amalgamation allows for the development of a cohesive body of research that can be easily followed.

The PhD thesis has continuous pagination, which can be seen at the bottom center of each page. For published documents, the original journal page numbers are also provided.

ABSTRACT

Desalination is an integral component of water supply for many cities and regions around the globe. Although, desalination can offer a rainfall independent source of water and provide social benefits, it is energy intensive compared to conventional water sources and can have significant impacts upon the environment. Therefore an interdisciplinary approach is required when planning for water supply by desalination. A life cycle assessment of a desalination supply chain can be integrated into an optimisation framework to simultaneously consider all possible planning alternatives and find the combination of planning decisions that optimizes environmental and economic objectives. This thesis aimed to develop a desalination supply chain optimization life cycle framework to analyze the economic and environmental impacts and trade-offs for alternative planning scenarios. The framework used life cycle assessment and a levelised cost model to quantify and compare the supply chain environmental and economic impacts for a range of planning scenarios. The framework incorporated a mixed integer linear programming model to determine optimal planning decisions such as water capacity expansion of each type of desalination technology over a planning horizon, and optimal locations of new desalination plants while considering interdependencies among water distribution and treatment processes. The framework was tested for future seawater reverse osmosis desalination planning in the northern metropolitan area of Perth, Western Australia over the next 20 years.

Results indicated that, a decentralised desalination supply system with small and medium-sized SWRO plants integrated into the Perth metropolitan area could achieve a lower environmental and economic impact, when compared to a centralised supply system with a large desalination plant located far from final demand. Improving seawater quality by introducing beach well intake - a mature intake technology for smaller-sized plants - could further promote the decentralised supply system environmental and economic performance. The capital expenditure contribution to total cost for the treatment facilities in the decentralised supply system was found to be higher than for the centralised supply system. However, this was outweighed by the significant water distribution pipeline construction and operational expenditure savings and also the operational expenditure savings associated with lower chemical and electricity use in the beach well plants. Construction phase contribution to treatment facilities life cycle environmental impact for the decentralised supply system was found to be higher than for the centralised supply system due to diseconomy of scale in smaller-sized plants. However, this was outweighed by significant water distribution pipeline construction and operational environmental impacts savings. Smaller plants with beach well intake benefit from operational environmental impact savings associated with lower chemical and electricity use. Multi-staged construction of successive small plants compared to single-stage construction of a large plant provided better economic outcomes due to lower interest costs. However, multi-staged construction led to higher environmental impacts associated with diseconomy of scale in the plant construction phase.

The case study provided numerous insights that were only possible through the use of a life-cycle optimization framework. For example, in desalination planning for a metropolitan area with land scarcity for siting new plants, the factors of supply system configuration, land-use patterns, environmental impacts and economic costs are highly inter-related and decision makers can consider these as a whole rather than considering each separately. The transparency and flexibility of the framework allows professionals from different disciplines to test the scenarios in a quantitative manner, to understand potential planning implications.

TABLE OF CONTENTS

LIST OF FIGURES

(This list includes figures in the text of this thesis and does not include figures in the published manuscripts)

LIST OF TABLES

(This list includes tables cited in the text of this thesis and does not include tables in the published manuscripts)

PUBLICATIONS

Shahabi, M. P., McHugh, A., Anda, M., & Ho, G Sustainable planning of desalination for metropolitan area (submitted to journal of Environmental Science and Technology).

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Shahabi, M. P., McHugh, A., Anda, M., & Ho, G., (2014) Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy, Renewable Energy, 67, 53-58.

Shahabi, M. P., Anda, M., & Ho, G., (2014) Influence of site-specific parameters on environmental impacts of desalination, Desalination and Water Treatment, DOI: 10.1080/19443994.2014.940653.

ABBREVIATIONS

ADP Abiotic Depletion Potential

AP Acidification Potential

EA Exergy Analysis

EP Eutrophication Potential

FAETP Freshwater Aquatic Ecotoxicity Potential

GWP Global Warming Potential

HTP Human Toxicity Potential

IPCC Intergovernmental Panel on Climate Change

ISO International Organisation for Standardisation

LC Levelised Cost

LCA Life Cycle Assessment

LCC Life Cycle Costing

LP Linear Programming

MAETP Marine Aquatic Ecotoxicity Potential

MED Multi-Effect Distillation

MILP Mixed Integer Linear Programming

MSF Multi-Stage Flash

NLP Nonlinear Programing

ODP Ozone Depletion Potential

POCP Photochemical Ozone Creation Potential

SETAC Society of Environmental Toxicology and Chemistry

SPI Sustainability Process Index

SWRO Seawater Reverse Osmosis

TETP Terrestrial Ecotoxicity Potential

UNEP United Nations Environment Programme

UNESDA Union of European Soft Drinks Associations

VC Vapour Compression

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CHAPTER 1. INTRODUCTION

This chapter outlines the background to the thesis, reasons why the study was undertaken, its aim, research objectives, and the way in which the thesis is organised.

1.1. Background

Water is required for fundamental human needs such as drinking, hygiene and providing food. Modern human society water demand is sharply increasing due to rapid urbanisation, increased industrialisation, and improving living standards. The Organisation for Economic Co-operation and Development OECD [1] recently projected that global water demand for fresh water will increase by 55% by 2050, mainly due to growing demands from manufacturing, thermal electricity generation and domestic use [1]. Moreover, water supply to cities in a rapidly urbanizing world is challenging [2]. In 2014, 54% of the global population lived in cities and it is expected that this proportion will increase to 67% by 2050 [3]. Conventional water resources such as surface water and groundwater sources have been depleted in many metropolitan areas, and cities are developing innovative solutions such as integrated urban water management or/and employing more advanced technologies such as membrane technology for desalination, or using reclaimed water to meet their demands. Although these advanced technologies could offer a rainfall independent source of water and provide social benefits, they are energy intensive in comparison to conventional water resources and they have detrimental impacts upon the environment. Therefore an interdisciplinary approach is required when planning for sustainable water supply employing advanced treatment technologies.

1.2. Desalination

1.2.1. Desalination technologies

Desalination has a long history of supplying clean water in arid environments such as the Middle East, and islands in the Caribbean and Mediterranean. However, recent ever-changing climate patterns caused by global warming, population growth, limited availability of terrestrial water sources has extended the use of this water source to all over the world. Thus, desalination capacity has been growing worldwide and will continue to grow. It is expected that a significant contribution to the new capacity growth will come from development of seawater desalination plants. This is because brackish aquifers have finite capacity and rate of recharging, while seawater is drought proof and essentially infinite. Moreover, approximately three billion people — about half of the world's population — live within 200 kilometres of a coastline [4], so seawater is an accessible resource. Currently, seawater is the most common feedwater for desalination. 59% of the installed capacity worldwide is seawater desalination, while 22% is brackish water [5].

The two most common seawater desalination technologies are thermal distillation and membrane desalination. In thermal distillation, freshwater is separated from the feedwater by evaporation, while in membrane desalination; freshwater is separated from the feedwater by using a semipermeable membrane. Multi-stage Flash (MSF), Multi-effect Distillation (MED) and Vapour Compression (VC) are common types of thermal distillation and Reverse Osmosis (RO) is common type of membrane desalination for seawater. The fundamentals of MSF, MED, VC and RO desalination have been well reported in the literature [6].

Desalinated water has variety of uses including municipal, industrial, electrical production, irrigation, tourism, and army types. According to the IDA desalination yearbook 2013-2014, 60% of the total world installed capacity is used in the municipal sector and 28% of it is used in industrial sector [5]. In 2013, IDA reported that 65%, 22% and 8% of the worldwide desalination capacity was RO, MED and MSF respectively [7]. The high use of RO technology is because of its competitive water production cost, energy consumption and improved membrane durability compared to other desalination technologies. However, there are concerns over seawater reverse-osmosis (SWRO) desalination high environmental impacts and production costs when compared with traditional water sources.

1.2.2. Desalination planning

Desalination planning is the activity of defining the size, location and the scope of the desalination project and to chart the roadmap for project implementation. In brief the planning considerations include the following [6].

- Plant service area, capacity and site
- Intake type and location
- Source water quality

- Product water quality
- Plant discharge
- Conceptual plant design
- Project implementation schedule and phasing
- Project economics
- Contractor procurement for project implementation
- Project funding

Usually strategic planning for construction or expansion of desalination systems involves evaluation of a number of alternatives for the key project components to maximise the economical and social return of the investments. The key project components encompass source water intake, concentrate discharge, pre-treatment facilities, system process, post-treatment facilities, and product water distribution system.

A long-term desalination planning for urban supply is a challenging task with uncertainties associated with water demands and availability of other rainfall dependent sources. Seawater desalination is energy intensive and operational costs of plants which are powered by fossil based energy could also be influenced by global energy crises. Integrating new desalination plants into existing urban areas is another planning challenge. As desalinated water source becomes part of a water supply system, optimal decisions should be made for energy source, locating and sizing water distribution system infrastructures in order to deliver water from treatment source to demand areas in economic and sustainable way. The decisions are complex requiring computational framework for optimal planning solutions.

Recently, the terminology of "desalination supply chain" is introduced for the first time by Al-Nory, Brodsky [8]. This new terminology is introduced to encourage water supply planners to benefit from the existing theories in supply chain for desalination planning. The definition is as follows:

"The supply chain for water desalination includes all relevant supplies and materials, processes, and resources for producing water and for storing and distributing this water to meet the demand. The management of the supply chain focuses on the question of how best to match supply to demand. The value of the supply chain perspective comes from being able to plan or optimize at a system level rather than at a component or unit level, and hence, to obtain system plans or designs that are closer to being globally optimal. In essence, the supply chain perspective attempts to avoid sub-optimization."

An obvious recent trend in seawater desalination for urban water supply is the construction of larger-capacity plants, which has significant contribution in freshwater supply for coastal cities around the globe. Large desalination plants built between 2000 and 2005 were typically designed to supply only 5 to 10 percent of the drinking water of coastal cities, while today most regional or national seawater desalination projects in countries such as Spain, Australia, Israel, Algeria and Singapore are planned to meet 20 to 50 percent of their long term drinking water needs with desalinated seawater[6]. These large desalination plants enjoy economies of scale for the treatment facility. However, potential sites for constructing large plants need to meet specified criteria such as proximity to the ocean, access to a power source and minimal impact on environmentally sensitive areas [6]. In addition, obtaining environmental regulatory approvals for large plants and maintaining ongoing compliance can be challenging in developed countries with stringent environmental legislation and governance. Identifying sites that meet all of these criteria, while having enough acreage to accommodate large-scale plant components and safety buffers, is almost impossible in established urban areas. These barriers result in large desalination plants being constructed far from water demand and subsequently long water transportation distances compared to those that would apply if smaller plants located within the distribution network are used instead. This long water transportation could have environmental and economic burdens that need to be evaluated in the planning stage.

Water supply planners around the world are learning how complex their decisions regarding desalination planning can be in metropolitan areas; hence this research was undertaken to understand the opportunities that may exist in metropolitan desalination planning to improve the system environmental and economic performance.

1.3. Life cycle assessment

Life cycle assessment (LCA) is a systematic tool to analyse and assess environmental impacts of a product system throughout its life cycle. The forerunners of modern LCA can be tracked back to Resource

Environmental Profile Analyses in 1960s. In 1990s, the term “life cycle assessment” was proposed and agreed in a workshop in Vermont, USA held by Society of Environmental Toxicology and Chemistry (SETAC) and since then the term LCA has appeared in the literature. LCA use has become widespread and grown into a body of systematic, inclusive, analytical approaches to environmental impact assessment [9]. The updated international standards produced in 2006 include guidance on undertaking, reviewing and reporting LCA studies[10]. ISO14040 advises on principles and framework [11] while ISO14044 deals with issues for carrying out an LCA study such as data documentation [10].

There are other environmental impact assessment tools such as Sustainable Process Index (SPI) and Exergy Analysis (EA). SPI method evaluates the areas required to provide the raw materials and energy demand in a sustainable way. The method relates these areas to the area needed to supply a citizen with all possible services [12]. EA method, quantifies the sustainability of technological processes based on thermodynamics with energy carriers and materials expressed in the same calculable exergy [13]. The main advantage of LCA in comparison to these environmental assessment tools such as SPI [12] and EA [13] is that LCA is the only standardised method forming part of ISO standards.

Based on ISO14040 [11] framework, LCA is conducted in four phases. The first phase is “Goal and scope definition”. In this phase, the application of the LCA, intended audiences, functional unit, the most important methodological choices, assumptions and limitations are described. The second phase is “Inventory analysis”. In this phase, all environmental flows, including resource use inputs and pollution outputs are compiled. Inventory analysis is the most time consuming phase of an

LCA study. The third phase is "Impact assessment". In this third phase, inventory data are converted to impact results through use of appropriate algorithms in order to evaluate the magnitude and significance of potential environmental impacts of a product system. The fourth phase is "Interpretation" which includes critically reviewing the results in order to see if the conclusions are sufficiently supported by the data and procedures [9].

LCA has been applied in different industry sectors such as energy, water, transportation and manufacturing. LCA can assist in providing information about environmental burdens of products and services associated with any organisation. Application of LCA in the water industry started in late 1990s. These early works investigated and compared various processes for wastewater treatment [14], groundwater treatment [15], and seawater desalination [16]. The number of LCA studies have increased sharply since 2005 [17] .

Loubet, Roux [17] proposed a four-category classification for water technologies and distinguished between drinking water production plant, drinking water distribution network, waste water treatment plant and waste water collection network. An LCA study can include one or several water technologies. While since 1995, 100 LCA peer reviewed papers have included only one water technology in their LCA scope, there are 24 papers which have included more than one technology to investigate the whole water supply systems [17]. Amongst these studies, several LCA models have been developed to determine the environmental impacts associated with urban water supply system [18-30]. These models are able to estimate the environmental impacts of various water supply alternatives, and can also be employed to perform scenario analyses to quantify the environmental effects of modifications to the supply systems. Although these models are essential for facilitating a systematic analysis of water supply systems, they cannot simultaneously consider all possible water supply system alternatives to find the optimum solution. In order to tackle this issue in environmental analysis of water supply systems using LCA, in this thesis the LCA model has been integrated with mathematical optimisation techniques.

1.4. Mathematical optimisation

Water resources planners and managers assess and compare alternative water supply system designs or management plans considering systems economic, environmental, social and political performances. Models can be developed and employed to help planners assess the future economic, environmental, social and political consequences associated with alternative plans or management policies. Mathematical models contain algebraic equations which include variables that are known (parameters) and others that are unknown (decision variables) and to be determined. There are two types of common modelling approaches for the purpose of water supply planning: simulation modelling and optimisation modelling. For water supply planning and resources management, it is beneficial to employ both optimization and simulation modelling in different stages of the planning process. Optimization models could answer the question of what the best decision is. However, that solution is often based on many limited assumptions. Optimization models define a relatively small number of good alternatives that simulation models can later test, evaluate and improve these alternatives. The procedure of employing optimization models with the purpose of reducing the large number of plans and policies to a few that can then be simulated is called preliminary screening [31].

In general, a typical mathematical optimisation problem can be formulated as:

$$\begin{aligned} &\text{Minimise} && f(x) \\ &\text{Subject to} && h(x) = b \\ & && g(x) \leq 0 \\ &\text{Where} && x \text{ E X} \end{aligned} \qquad 1.1$$

Where f denotes an objective function, i.e. the function to be optimised; $h(x)$ is equality constraints, $g(x)$ is inequality constraints, and $x \mathcal{E} X$ is the decision variable. The optimal decision variable is searched within the feasible region determined by the model constraints within the subset X.

Mathematical programming problems can be divided into two main categories and distinguished between linear programming (LP) and nonlinear programming (NLP). LP represents the problems in which the objective function and all the constraints are linear functions of the variables. If amongst the objective function and the constraints at least one function is a nonlinear function of the variables, the problem is called NLP. If some of the variables are restricted to integer or discrete values in LP and NLP problems, the problem is called MILP and MINLP respectively. The work in this thesis uses MILP approaches to model and solve the desalination supply chain problem.

Since 1952 mathematical optimisation modelling has been employed as a strong tool in water resources planning [32]. These optimisation models addressed water allocation planning [32-42], water supply infrastructure planning [8, 43-50], regional wastewater allocation planning [50] and regional wastewater infrastructure planning [39, 51-53]. Amongst this literature, there is a lack of decision making tools designed for desalination planning except the recent works of [8] and [54].

Al-Nory, Brodsky [8] proposed a mathematical optimisation model to trace the plant location, technology type, capacity, operational considerations, distribution network structure and capacity. GHG emissions data of different desalination technology types were integrated in the model to include environmental considerations in the decision-making process, but they did not consider the pipeline system construction and operation GHG emissions in their analysis. In 2014, Saif and Almansoori [54] proposed multi-period MILP modelling to optimise the retrofit of water desalination supply chain. The model decision variables include new facility location and capacity expansion of water desalination supply chain infrastructure assets. The cost of CO_2 emissions was included in the analysis but construction phase emissions were excluded. Moreover in both works of

[8] and [54], there is lack of detailed environmental impacts data for various sizes of desalination plant and pipeline infrastructure which could lead to underestimation of smaller size plants and pipelines burdens associated with diseconomy of scale. Moreover, these two recent works have just included GHG emissions to air and have not considered supply chain emissions to water and land. This could create burdens shift between different environmental impact categories (e.g. climate change versus ozone layer depletion) or between supply system life cycle stages (e.g. construction phase versus operational phase). The application of LCA coupled with optimisation provides a powerful tool for satisfying environmental and economic objectives of the product system [55] and have being used in the range of planning problems. To our knowledge there are no desalination supply chain optimisation models that consider simultaneously costs and a range of life cycle environmental impacts.

1.5. Aim & scope of the research

Despite rapid advances in the past decades, there is still a large unexplored research area in the water supply planning especially due to the shift from dependency on traditional water resources to alternative water sources such as desalination. This thesis seeks to address the overarching research question:

How can desalination supply chain environmental impacts and costs be optimised as whole?

In answering this question, the main objective of the research was **to develop a desalination supply chain optimization life cycle framework to analyse the economic and environmental impacts and trade-offs for alternative desalination supply planning scenarios.** The modelling framework for this research, components of the framework and their related chapters are shown in Figure 1-1.

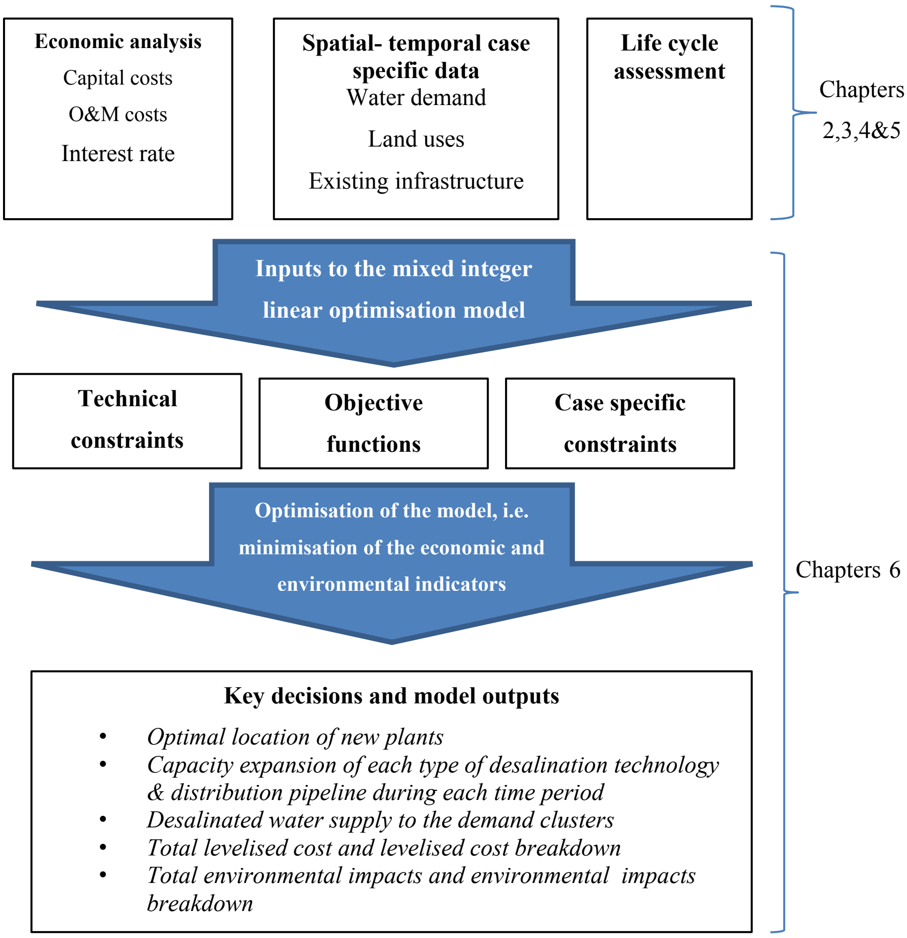

Figure 1-1 Modelling framework components and their related chapters

SWRO was chosen as the core technology of desalination as detailed assessment of more than one treatment technology was beyond the scope of this research. Two process configurations were selected: an open intake configuration in which a seawater reverse osmosis (SWRO) desalination plant employs open intake and membrane pre-treatment prior to RO, and a beach well process configuration in which feedwater is extracted from the subsurface using beach well intake and cartridge filtration prior to RO. Beach well intake is a mature intake technology for smaller-sized plants. The LCA scope is primarily cradle to gate. Each LCA covered the construction and operational phase of the SWRO plants and their connected storage tanks and pipelines. Economic cost analysis covered the costs of construction, operation and maintenance of the system.

1.6. Research objectives and thesis structure

Each chapter of this thesis was directed by the central research question and also a number of core questions and sub questions. The objectives and core research questions for each chapter of the thesis are presented below alongside a brief description on how they are structured within the thesis. The sub-questions and related literature reviews are presented in each of the corresponding chapters.

- **Quantify and compare the life cycle environmental performance of SWRO desalination plant powered by renewable energy and fossil based grid (Chapter 2)**

Chapter 2 addresses the first core research question, namely, **what are the influences of power supply model on the life cycle environmental performances of a Seawater Reverse Osmosis (SWRO) desalination supply chain?** First, a critical literature review of previous LCA studies on desalination supply system was provided to highlight the needs for quantifying supply chain contributions to the overall environmental impact associated with renewable energy powered desalination plants. A LCA of SWRO desalination plants powered by renewable energy is conducted and compared with those powered by fossil based grid electricity in Chapter 2. The publication below arises from the work in Chapter 2.

Shahabi, M. P., McHugh, A., Anda, M., & Ho, G. (2014). Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renewable Energy, 67, 53-58.

- **Quantify and compare the life cycle environmental and economic performance of SWRO desalination plant using beach well intake and open intake facilities for extracting feedwater (Chapter 3).**

Chapter 3 addresses the second core research question, namely, **what are the influences of feedwater quality on the life cycle environmental and economic performance of a Seawater Reverse Osmosis (SWRO) desalination supply chain?** This chapter provides relevant literature on application of subsurface intakes in small desalination plants, and review previous studies on application of LCA in SWRO process optimisation to highlight the needs for quantifying the environmental and economic performances of SWRO plants with beach well intakes. A LCA and LC analyses of SWRO desalination plants employing beach well intakes are conducted and compared with those employing open intakes in Chapter 3. One publication arises from the work in Chapter 3.

Shahabi, M. P., McHugh, A., & Ho, G. (2015). Environmental and economic assessment of beach well intake versus open intake for seawater reverse osmosis desalination. Desalination, 357, 259-266.

- **Quantify and compare the GHG emissions of centralised and decentralised SWRO desalination options (Chapter 4).**

Chapter 4 addresses the third core research question, namely, **do SWRO desalination plants size and location affect on the life cycle environmental performances of their supply chain?** In Chapter 4 a Geographical Information System (GIS) based method is introduced to assist in desalination planning. The method's applicability was tested using data for the northern corridor of Perth, Western Australia (WA). Two scenarios of centralised and decentralised seawater desalination options were compared based on their life cycle GHG emissions. The publication below arises from the work in Chapter 4.

Shahabi, M. P., Anda, M., & Ho, G. (2014). Influence of site-specific parameters on environmental impacts of desalination. Desalination and Water Treatment, (ahead-of-print), 1-7. DOI:10.1080/19443994.2014.940653

- **Quantify and compare the life cycle environmental and economic performance of centralised and decentralised SWRO desalination options (Chapter 5).**

Chapter 5 addresses the forth core research question, namely, **what are the influences of SWRO desalination plants size and location on the life cycle environmental and economic performances of a desalinated**

water supply system? In this chapter, a framework for investigating the optimum geographical scale for water planning using spatial and temporal case study data (e.g. land availability, water demand, and existing pipeline network) coupled with hybrid LCA and LC analyses is provided. The method's applicability was tested using data for the northern corridor of Perth, Western Australia (WA). One centralised desalination supply system and two decentralised seawater desalination options were compared. The manuscript below arises from the work in Chapter 5 which is under review.

Shahabi, M. P., McHugh, A., Anda, M., & Ho, G. (2015). Comparative economic and environmental assessments of centralised and decentralised seawater desalination options (in press).

- **Multi-period mixed integer linear optimisation framework for life cycle assessment –based desalination supply system planning (Chapter 6)**

Chapter 6 presents the first life cycle-based framework to optimize the treatment, storage and delivery of desalinated water to final demand areas in metropolitan area by minimizing cost or environmental impacts while considering technological and case specific constraints. This chapter addresses the fifth main research question, namely, **Does application of the quantitative framework in desalination planning facilitate improved environmental and economic performance of the supply chain compared with Business as usual practises?** A real case study of desalination planning in Perth, Western Australia is employed to demonstrate the applicability of the proposed modelling framework. The case study provided numerous insights that were only possible through the use of a life-cycle optimization framework such as trade-offs associated with different environmental and economic objectives. Model parameters and constants were obtained from Chapters 2, 3, 4 and 5. One publication arises from the work in Chapter 6.

Shahabi, M. P., McHugh, A., Anda, M., & Ho, G. (2015). Planning for sustainability of seawater desalination infrastructure for metropolitan areas. Will be Submitted to Environmental Science and Technology in September 2015.

- **Conclusions and recommendations for future research (Chapter 7)**

In Chapter 7 conclusions and recommendations for the future research are provided.

1.7. Justification

The life cycle optimisation model developed in this work enables single-objective optimisation based on either economic cost or environmental objective functions, allowing for their trade-offs to be explored. Aggregation of economic costs and environmental impacts could be observed in previous literature [54] through incorporating the aggregated costs of the environmental impacts in cost objective. Aggregation of objectives gives a single solution to a problem but suffer from uncertainties associated with estimates of externalities. Moreover, such an approach obscures the trade-offs between range of cost and environmental objectives to be explored. The disaggregated method included in this study help understand trade-offs between different objectives and inform better the future policy debates.

CHAPTER 2. QUANTIFY AND COMPARE THE LIFE CYCLE ENVIRONMENTAL PERFORMANCES OF SWRO DESALINATION PLANT POWERED BY RENEWABLE ENERGY AND FOSSIL BASED GRID

2.1. Attribution

Maedeh P. Shahabi wrote all sections of this paper, carried out all LCA modellings and conducted all data analysis. Adam McHugh acted as co-supervisor and provided significant feedback into the EIO-LCI model developed by Maedeh P. Shahabi. He also provided feedbacks to LCA method and sensitivity analysis. Goen Ho acted as co-supervisor and supervised designing the scenarios. He also read various drafts of papers and provided feedback regarding the scope of the study. Martin Anda acted as principal supervisor and helped in revising Perth case study data through communication with Water Corporation. He also revised several drafts of the paper and gave feedbacks on the case study data.

Maedeh P. Shahabi: +80%

2.2. Paper 1 : Shahabi, M. P., McHugh, A., Anda, M., & Ho, G. (2014). Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renewable Energy, 67, 53-58.

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Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy

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ABSTRACT

This paper evaluates life cycle Greenhouse Gas (GHG) emissions of a Seawater Reverse Osmosis (SWRO) desalination plant and assesses its performance under three power supply scenarios. A Life Cycle Assessment (LCA) analysis is conducted for a plant located in Perth, Western Australia (WA). Input and output flows of SWRO plant are based on literature and Perth desalination plants. The Simapro Australian and Ecoinvent databases are used for operational phase Life Cycle Inventory (LCI). An LCI for the construction phase of the plant is developed using economic input–output analysis. Electricity supply scenarios are "100% WA grid", "100% wind energy" and "92% wind energy plus 8% Photovoltaic (PV) solar energy". Results indicate that renewable energy powered desalination plants achieve GHG emissions reduction of ~90% compared to the plant powered by WA grid scenario. For the plant powered by fossil based grid electricity, electricity use in the operational phase is found to be responsible for more than 92% of its GHG emissions. On the other hand, for the plants powered by renewable energy, the highest contribution belongs to chemical use in the operational phase (60%) followed by the construction phase (17%). Indirect emissions due to the electricity consumption in the chemical, wind turbine and PV solar panel manufacturing are found to contribute the lion's share (36–39%) of the life cycle emissions for the renewable energy powered desalination plants. Any improvement in fuel mixes in grid electricity towards cleaner energy sources can be beneficial by reducing impacts associated with upstream electricity use in manufacturing. This work provides the first reference to identify and quantify supply chain contributions to the overall environmental impact associated with renewable energy powered desalination plants.

1. Introduction

The recent combination of climate change related rainfall reduction and rapid population growth in southwest Western Australia (WA) has posed great challenges for the balancing of water supply and water demand in that region. The state's Water Corporation forecasts water shortfalls for Perth and surrounding areas of around 331 GL annually by 2030 [1]. Water use restrictions, increased water recycling and development of new water sources are identified as strategies for securing reliable water supply in a drying climate. The most significant supply-side proposal involves the construction of Seawater Reverse Osmosis (SWRO) desalination plants on the northern and southern seaboard of the Perth metropolitan area. This technology could contribute nearly 50% of new water source development by 2030 [1]. Moreover, half of the water supply for the area is currently sourced from two large SWRO plants [2]. To increase sustainability of this climate resilient water source, desalination plants in Perth are "paired" with wind and solar farms (Table 1). Water Corporation purchases the desalination plants electricity demand from three wind and solar farms annually and consumes the equivalent amount of electricity from WA grid electricity [2,3].

Powering desalination plants with renewable energy instead of the fossil based grid electricity reduces the desalination plants Greenhouse Gas (GHG) emissions. Comparing GHG emissions of the desalination plants powered by renewable energy with centralised water supply systems that use mixes of water sources including desalination, shows that the desalination alone is much more GHG intensive. The objective of this study is to identify and demonstrate the main sources of GHG emissions within the life cycle of desalination plants powered by renewable energy and compare their performance with those powered by fossil based grid electricity. Identification and quantification of supply chain contributions to the overall environmental impact associated with

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Table 1
Desalination plants and their energy sources in Perth.

Name	Plants capacity	Paired renewable source
Perth Seawater Desalination Plant	45 GL/year	Emu Downs Wind Farm [3]
Southern Seawater Desalination Plant (SSDP)	50 GL/year first phase and 50 GL/year second phase	Greenough River Solar Farm and Mumbida Wind Farm [2]

If two phases of the SSDP plant run at full capacity, the claimed renewable sources could not meet the energy demand of the plant. Second phase electricity supply strategy for SSDP is under review.

renewable energy powered SWRO are prerequisites in the development of strategies to reduce such impacts. Yet, the authors are unaware of any previous Life Cycle Assessment (LCA) studies of renewable energy powered SWRO plants that have provided contribution analysis. Through environmental impact assessment of the system, possibilities for further reducing the GHG emissions of plants powered by renewable energy source are identified.

The paper begins with brief review of the existing literature on the LCA of SWRO before presenting the LCA methodology and system boundary used.

2. Literature review

Although seawater desalination is one of the most climate resilient water sources, there are concerns over its potentially high environmental impact. Life cycle assessment (LCA) provides a comprehensive, ISO standardised method for evaluating such impacts [4]. Recently, LCA has been applied to investigate the environmental impacts of SWRO plants, mostly for the comparison of SWRO with other water sources and technologies [4–12]. Several of these studies identified the significant role of electricity consumption in the total life cycle environmental impact of SWRO powered by fossil based grid electricity. Raluy et al. [6] and Stokes et al. [9] found that the overall environmental impact of SWRO plants is significantly affected by their electricity supply fuel mix. Raluy et al. [6] compared Spanish, French, Norwegian and Portuguese models of electricity production on the life cycle airborne emissions associated with desalination technologies and concluded that the renewable energy based Norwegian grid produced the lowest emissions of the four by a substantial margin. Stokes et al. [9] compared six different electricity mixes – "California's average electricity mix", the "US national mix", "Solar PV", "Solar thermal", a "European Union 2020 mix" and a "hypothetical low emission mix" – for desalination, importation and recycling-based water sources. They found that electricity production models with a higher share of renewable energy decreased the environmental impact of all water source categories. Biswas [10] accounted for the operational phase greenhouse gas (GHG) emissions of an SWRO desalination plant in Perth, WA using LCA method and proposed wind power as a GHG reduction strategy. GHG emission values associated with SWRO supply options in previous studies are summarised in Table 2. Although GHG emissions of SWRO powered with renewable energy have been accounted [9,10], no identification and quantification of supply chain contributions to the overall GHG emissions associated with renewable energy powered SWRO has been made. This information can be used to discover possible decisions to improve the supply chain of SWRO desalination plants powered by renewable energy. Another novelty of this study lies in the use of an economic input–output LCI method for accounting GHG emissions of construction phase of the desalination plant.

3. Materials and methods

The method applied ISO14040 [13], with LCA conducted in four stages: goal and scope, inventory analysis, impact assessment, and interpretation. The sections that follow reflect this structure, with the first three stages described under headings of the same name.

3.1. Goal and scope

The first goal of this study is to provide life cycle GHG emissions quantification of an SWRO desalination plant powered by Scenario A "100% Western Australia grid", Scenario B "100% wind energy", and Scenario C "92% wind energy plus 8% solar PV". Scenarios B and C are electricity production models for powering SWRO desalination plants in Perth, WA (Table 2). The second goal is to identify and demonstrate the main sources of GHG emissions within the life cycle of the desalination plant. The functional unit for the study is one cubic metre of water, treated and distributed to a population centre. The scope of this study is primarily cradle to gate. More specifically, each Life Cycle Inventory (LCI) covers the construction phase and the operational phase for SWRO plants, with some coverage of the disposal phase for high impact inputs. The input flows analysed were chemical use, materials consumed for membrane replacement and electricity consumption associated with seawater extraction, water treatment and the distribution of desalinated water to final users. Disposed waste of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged streams to sewer due to 'clean in place' and chemically enhanced backwash, discharged brine to sea were also covered. The decommissioning of the system was not considered.

Table 2
GHG emissions associated with SWRO in the previous studies.

Electricity production model	System boundary	Electricity use (kWh/m^3)	kg CO_2 eq. emissions per m^3	Reference
Union for co-ordination of transmission energy electricity mix	Operational phase	2.50	1.40	Hancock et al., 2012 [12]
Singapore electricity mix	Construction and operational phase	3.90	2.20	Zhou et al., 2011 [11]
Western Australia electricity mix	Operational phase	–	3.80	Biswas, 2009 [10]
100% wind	Operational phase	–	0.32	Biswas, 2009 [10]
U.S. average mix	Construction and operational phase	5.10	3.95	Stokes et al., 2009 [9]
100% solar PV generation	Construction and operational phase	5.10	0.72	Stokes et al., 2009 [9]
100% solar thermal generation	Construction and operational phase	5.10	0.45	Stokes et al., 2009 [9]
European Union 2020 mix	Construction and operational phase	5.10	1.93	Stokes et al., 2009 [9]
Spain electricity mix	Construction and operational phase	–	1.9	Muñoz et al., 2008 [4]

Table 3
System assumptions and description.

	Assumptions	Descriptions
SWRO desalination plant		
Productivity	50 GL annually	Similar to SSDP.
Capacity factor	0.85	Adopted from Ref. [19].
Pre-treatment	Membrane pre-treatment	Similar to SSDP
Water distribution distance	75 km between plant and centre of demand area.	Similar to SSDP.
Distribution head loss	3 metre per kilometre	[20]
Treatment process electricity use	3.5 kWh/m^3	[21]
Membrane material	–	Adopted from Refs. [12,22]
Chemical use, waste disposal, material transportation	–	Adopted from Ref. [10] similar to SSDP
Infrastructure capital cost	0.19 $AU/$m^3$	[19,23]
Plant life time	30 years	–
Wind farm		
Wind Turbine manufacturing	Manufactured in Europe	Adopted from Ref. [24]
Capacity factor	30%	Adopted from Ref. [24]
Life time	30 years	Adopted from Ref. [24]
Transmission network distance	400 km between the paired wind farm and the desalination plants	Similar to SSDP.
PV solar farm		
PV solar panel manufacturing	Manufactured in Europe	Adopted from Ref. [24]
Capacity factor	11%	Adopted from Ref. [24]
Life time	30 years	Adopted from Ref. [24]
Transmission network distance	400 km between the paired PV solar farm and the desalination plants	Similar to SSDP.

The descriptions for the desalination plant and the energy sources are listed in Table 3.

3.2. Life cycle inventory analysis method

A life cycle inventory (LCI) is the phase of LCA aimed at compiling all output emissions and wastes and also input resources as environmental flows [14]. In this study, LCI for construction phase was defined by economic input–output based (IO-based) LCI method. For operational phase, LCI was obtained by process based LCI method. Using economic input–output for construction phase was due to the process data limitation. The foreground data for the construction phase and operational phase are in monetary and physical unit, respectively. Operational phase background data was obtained from available libraries in Simapro software [15]. Data were mostly selected from Australian database and the grid electricity and transportation were selected for WA. For material and processes, which were not available in Australian database, Ecoinvent library was used as a supplement database.

Construction phase background data were calculated by following Economic IO-based LCI model [16] and matrix calculations were conducted with Matlab software.

$$Q = N \cdot \boldsymbol{x}^{-1} \tag{1}$$

$$A = Z \cdot \boldsymbol{x}^{-1} \tag{2}$$

$$Q* = Q(I - A)^{-1}, \tag{3}$$

where

$N = [n_{kj}]$ is a matrix of "Ecological Commodity Output", n_{kj} indicates the amount of ecological commodity output k associated with the output of sector j in physical unit.

$x = [x_i]$ is a vector of "Total Output", x_i indicates the total industry output summation of output consumed by intermediate industries, final users and exports, x is diagonal matrix with the elements of x strung out along its main diagonal.

$Z = [z_{ij}]$ is a matrix of "Interindustry Transactions", Z_{ij} indicates the amount of output from industry sector i used by industry sector j in monetary unit.

$I = [i_{ij}]$ is an identity matrix.

$Q^* = [q_{ij}]$ is a matrix where q_{ij} reflects the amount of ecologic output i associated with delivering a dollar's worth of industry j output to final demand directly and indirectly.

The "Interindustry Transactions" and "Total Output" matrix were obtained from latest 2008–2009 industry by industry flow table published by Australian Bureau of Statistics [17]. There are 111 industry sectors, which make a Z matrix of 111×111. The sector of "Non-Residential Building Construction" (NS) was selected to represent construction of the water supply system. The primary data for "Ecological Commodity Output" matrix was obtained from "National Greenhouse Gas Inventory" [18] with database consisting of 12 pollutants to air. The emissions associated with delivering one 2009 $AU worth of NS industry sector were computed and exported to Simapro software as background data for construction phase.

3.3. Life cycle impact assessment method

Life cycle impact assessment (LCIA) is the final phase of LCA in which inventory data are converted into impact results through the use of appropriate algorithms or indicators, to simplify understanding and assessing the environmental impact of a product system [14]. GHG emissions in kg CO_2 equivalent were calculated based on the International Governmental Panel on Climate Change (IPCC) 2007 method for the timeframe of 100 years with Simapro software [15].

4. Results and discussion

4.1. Baseline comparative LCIA of scenarios

The normalised GHG emissions of the three scenarios are shown in Fig. 1. Scenarios B and C are normalised by the maximum value observed in Scenario A. Results in Fig. 1 indicated that the desalination plants powered by renewable sources (Scenarios B & C) produced a similar degree of emissions, while the plant powered by fossil based grid electricity produced nearly 90% higher emissions. Moreover, the results showed that in Scenario C, replacing 8% of the

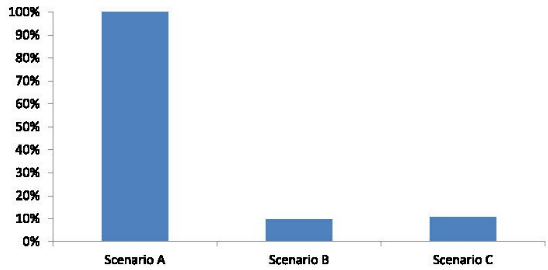

Fig. 1. Relative impact of Scenarios A, B and C. The maximum values observed for GHG emissions for Scenarios A, B and C are 4.61, 0.446 and 0.491 kg CO_2 eq. per m^3 water produced, respectively.

wind energy with the PV solar in the energy scheme, increased the emissions by 1% compared to Scenario B.

It is worth noting that the emissions associated with the plant powered by WA grid in this study are higher than Biswas, 2009 study [10]. This is due to the fact that the system boundaries of the studies are different. Biswas, 2009 accounted GHG emissions associated with operational phase, while in this study construction phase and distribution pumping are also included. In addition, GHG emissions of the desalination plant in this study and Biswas [10] are higher than plants located in Singapore [11] and Europe [4,12], mostly due to the different grid fuel mixes. Western Australia, Singapore, and UCTE grid electricity fuel mixes consist of more than 90% (mostly hard coal and natural gas), 95% (mostly natural gas), 40% (mostly hard coal and natural gas) fossil fuel, respectively. Although there is some variance in the previous literature results, systems powered by renewable sources consistently appear as the lowest GHG producing options.

4.2. Contribution analysis

According to ISO14044 standard [13], identifying key materials and processes with the dominant environmental impacts during the life cycle of systems has a significant role in interpretation phase of LCA studies. This section provides detailed contribution analysis of the desalination plant GHG emissions for three electricity production scenarios (Fig. 2).

The electricity uses in the treatment and distribution processes for Scenario A is shown to be the dominant factor, which is responsible for more than 92% of the GHG emissions contribution. This is due to the electricity production model in Scenario A, which is mostly fossil fuel based. Further detailed contribution analysis was conducted to identify the key sub-processes for WA grid electricity. Results showed that the high contribution of the GHG emissions from WA grid electricity is associated with coal burning activities in power plants. For Scenario B, powered by wind source, electricity use is the second most significant contribution (20%). Within the electricity sourced by wind farm, wind plant moving parts, fixed part, electricity transmission facilities and gear oil have the contribution of 42%, 36%, 20%, and 2% respectively. High contribution of wind turbines production in the life cycle of the wind farm was also highlighted in previous LCA studies [25,26]. In Scenario C, the contribution of the electricity emissions in total life cycle increases by 27% compared with Scenario B. This is due to the fact that the PV solar farm emits higher GHG emissions per kWh electricity produced compared with wind farms electricity in this study. Detailed contribution analysis within the electricity sourced by PV solar farm system showed that solar modules, rolled steel and concrete facilities and transmission facilities have the contribution of 62%, 30%, 3% and 5% respectively.

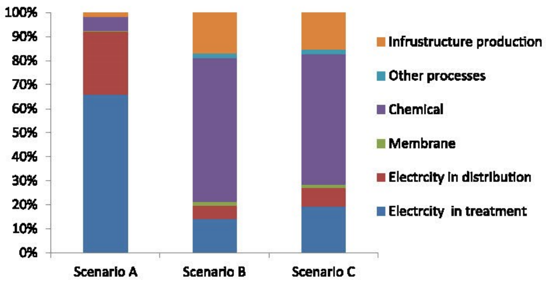

Fig. 2. Contribution analysis of subsystems to the life cycle GHG emissions for Scenarios A, B and C.

In these three scenarios, the chemical use is responsible for emission of 0.267 kg CO_2 eq. per m^3 water produced. The chemical use accounts for 6% of GHG emissions in Scenario A. This is the second significant contribution after electricity use. For Scenarios B and C, powered by the renewable sources, chemical use is the major contributor, accounted for 60% and 54% of GHG emissions in the life cycle of the systems. Within the chemical use subsystem, transportation of the chemical from the chemical manufacturing plant to the desalination plant has less than 4% contribution while, nearly 48% of the GHG emission emits from the fossil based grid electricity used in the chemical manufacturing.

The infrastructure construction phase of the desalination plant emits 0.0754 kg CO_2 eq. per m^3 produced water in the three scenarios. The construction phase is accounted for 2% contribution of the total life cycle GHG emissions in Scenario A. This contribution increases to 17% in Scenario B and 15% in Scenario C, which makes their construction phase impacts the third significant contributors in their total life.

Two subsystems of membrane material consumption plus other processes (waste and wastewater management) contribute to less than 1% GHG in Scenario A, 4% in Scenario B and 3% in Scenario C.

Generally, in Scenarios B and C, the chemical consumption is the sub-process with the highest GHG emissions while in Scenario A the highest contribution belongs to electricity consumption in the treatment and distribution processes. Results highlighted consequences of high chemical use in SWRO desalination plants regarding their life cycle GHG emissions. While the previous studies mainly emphasised on the importance of electricity use in GHG emissions of desalination plants, these findings showed the importance of chemical use in desalination plants powered by renewable sources. This means that optimisation of the SWRO treatment process to either reduce the amount of chemical use or consume more environment friendly chemicals can further improve the environmental performance of desalination plants.

4.3. Upstream electricity in manufacturing

More detailed analyses were conducted to further identify the role of material manufacturing electricity use in GHG emissions of the desalination plants powered by renewable energy (Table 4). The results indicated the significant contribution of upstream electricity use in the desalination plant life cycle GHG emissions (36.1% in Scenario B & 39.8% in Scenario C). The contribution of the electricity in chemical manufacturing is shown to be the dominant factor for both scenarios. For Scenario B powered by wind energy, electricity required for the wind turbine manufacture is the second most significant contribution. When the PV solar sources included in the energy production model in Scenario C, the upstream electricity use in the PV solar manufacture becomes the second greatest contribution and the wind turbine manufacture moves to the third. This is due to the fact that PV solar module manufacture is more electricity intensive in compared to wind turbine manufacture. In both scenarios, contribution of membrane modules manufacturing is insignificant.

Results highlight high contribution of material manufacture electricity use in GHG emissions of SWRO desalination plants powered by renewable sources. This means that life cycle GHG emissions of SWRO desalination plants are highly influenced by GHG emissions of electricity use in material manufacturing. Any improvement in electricity production scheme for material manufacturers toward cleaner energy sources can be beneficial.

Table 4
The electricity use and the GHG emissions contribution of the material manufacturing under 30 years water supply system life time.

Scenario		Wind farm material	PV solar farm material	Chemical	Membrane modules
B	Electricity use (kWh/m^3 water produced)	0.017	–	0.154	0.001
	Contribution in total life GHG emissions	2.8%	–	33.5%	0.2%
C	Electricity use (kWh/m^3 water produced)	0.016	0.014	0.154	0.001
	Contribution in total life GHG emissions	2.1%	7.4%	30.2%	0.1%

Table 5
GHG emissions sensitivities based on deviation of ±50% for variables.

Scenario	Water distribution distance	Electricity transmission distance	Material transportation distance	Electricity use in treatment process	Chemical use in treatment process
A	±13.23%	–	±0.22%	±32.97%	±3.04%
B	±3.00%	±1.66%	±0.76%	±7.26%	±30.78%
C	±4.15%	±1.51%	±0.96%	±9.85%	±27.96

4.4. Sensitivity analysis

A sensitivity analysis was carried out to find out to what extent the life cycle GHG emissions of the desalination plant is influenced by site-specific factors (water distribution, electricity transmission and material transportation distance) and also the process specific factors (electricity and chemical use in treatment process) in the three scenarios (Table 5). The sensitivity was calculated based on deviation of ±50% even though for process specific factors this may not be realistic. The analysis showed that the GHG emissions of the desalination plant powered by fuel based electricity are more sensitive to the electricity use, while GHG emissions of the renewable sourced plants are more sensitive to the chemical use. This is consistent with the previous discussion (Section 4.2) on the differences between contribution analysis results of the plant powered by fossil based grid electricity and the plants powered by renewable sources. Additionally, Scenario C is more sensitive to the electricity use than Scenario B. This is due to the fact that the 8% PV solar source in Scenario C produces more GHG than the same amount of wind source in Scenario B.

Amongst the site-specific factors, results are more sensitive to the water distribution distance. The GHG emissions are however less sensitive to change of the electricity transmission distance and material transportation. This is because these two subsystems produce a small portion of the total GHG emissions. Electricity for water pumping emits water distribution process emissions. Electricity transmission system emissions are due to the transmission network infrastructure. Generally, any location optimisation in order to reduce water distribution and electricity transmission emissions can be beneficial.

5. Conclusion

The results of this study are in agreement with the previous studies that GHG emissions of seawater desalination plants decrease by powering the plants with renewable energy instead of fossil based electricity. Uniquely, identification and quantification of supply chain contributions to the overall GHG emissions associated with renewable energy powered SWRO were conducted in this study using LCA method. Results indicated that GHG emissions of plants powered by renewable sources are highly dependent on chemical use in treatment process. The second most significant GHG emission contributors are wind and PV solar farm subsystems. Moreover, detailed contribution analysis discovered that indirect emissions due to the electricity consumption in chemicals, PV solar panels and wind turbines manufacturing stage are found to contribute to the lion's share of the life cycle emissions for the renewable energy powered desalination plants. However, one should consider the dependency of this finding on the geographical location of the material manufacturer that effects the GHG emissions of the upstream electricity used in the manufacturing. Finally, minimising water distribution and electricity transmission distance will reduce the GHG emissions of the system.

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2.3. Chapter summary and link to next chapters

This chapter addresses the first research question, namely, what are the influences of power supply model on the life cycle environmental performances of a Seawater Reverse Osmosis (SWRO) desalination supply chain. A Life Cycle Assessment (LCA) analysis was conducted for a plant located in Perth, Western Australia (WA). Electricity supply scenarios are "100% WA grid", "100% wind energy" and "92% wind energy plus 8% Photovoltaic (PV) solar energy". The power supply scenarios are electricity production models for powering two SWRO desalination plants in Perth, WA in 2013. Input and output flows of SWRO plant are based on literature and Perth desalination plants. The Australian process-based databases are used for facilitating all background data for all the sub-systems except membrane material and infrastructure production sub-systems. Membrane material background data were obtained from Ecoinvent due to lack of availability of related data in Australian databases. This assumption is not of significance due to the low contribution (less than 4%) of environmental impacts associated with membrane material use in life cycle of the system. A LCI for the infrastructure production of the plant is developed for the first time for Australian "Non-Residential Building Construction" economy sector using economic input-output analysis. This LCA provides the first reference to identify and quantify supply chain contributions to the overall environmental impact associated with renewable energy powered desalination plants. Results show that the desalination plant supply chain is highly influenced by energy source. In the scenarios in which the plant powered by renewable energy (Wind and

Solar), the chemical consumption is the sub-process with the highest GHG emissions. In this chapter, we focused on discussion on life cycle GHG emissions as an environmental indicator. Although the model allows for accounting other environmental indicators, the GWP is chosen for discussion because climate change is the main driver in shifting from fossil based grid to renewable energy for powering desalination plant in Australia. These LCA results show that regardless of desalination plants power supply model, any improvement in reverse osmosis process towards lower chemical use can be beneficial by reducing impacts associated with upstream chemical manufacturing (addressed in Chapter 3). Given that energy source is an important contributor to the life cycle environmental performance of desalination plants supply chain, it is selected as one of the key decisions which is investigated by our developed desalination supply chain decision optimization model in chapter 6.

CHAPTER 3. QUANTIFY AND COMPARE THE LIFE CYCLE ENVIRONMENTAL AND ECONOMIC PERFORMANCES OF SWRO DESALINATION PLANT USING BEACH WELL INTAKE AND OPEN INTAKE FACILITIES FOR EXTRACTING FEEDWATER

3.1. Attribution

Maedeh P. Shahabi wrote all sections of this paper, carried out all LCA and LC modellings, designing conceptual scenarios and conducted all data analysis. Adam McHugh acted as co-supervisor and provided significant feed-back into the LCA and LC methodology developed by Maedeh P. Shahabi. Adam McHugh also helped in language editing of the paper. Goen Ho acted as co-supervisor and designed the concept for the paper. He also read various drafts of papers and provided feedback regarding the scope of the study consist of scenario development and sensitivity analysis. Martin Anda acted as principal supervisor and revised various drafts of the paper and gave feedbacks on case study data.

Maedeh P. Shahabi: +80%

3.2. Paper 2: Shahabi, M. P., McHugh, A., & Ho, G. (2015). Environmental and economic assessment of beach well intake versus open intake for seawater reverse osmosis desalination. Desalination, 357, 259-266.

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Environmental and economic assessment of beach well intake versus open intake for seawater reverse osmosis desalination

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HIGHLIGHTS

- Life cycle assessment of the SWRO desalination plant with beach well intake
- Life cycle assessment of the SWRO desalination plant with an open intake
- Plant with beach well intake results in up to 31% less environmental impact.
- Plant with beach well intake results in 13% lower total costs.

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Economic analysis

ABSTRACT

This paper presents a comparative life cycle assessment (LCA) and levelised cost (LC) analysis of two scenarios: an *open intake scenario* in which a seawater reverse osmosis (SWRO) desalination plant employs an open intake and membrane pre-treatment prior to RO, and a *beach well scenario* in which feedwater is extracted from the subsurface using beach well intake and cartridge filtration prior to RO. In both scenarios, desalination plants with 35,000 m^3/day capacities were modelled. Results indicate that the beach well intake plant life cycle environmental burdens and LC were as much as 31% and 13% lower respectively, compared with the open intake plant. A detailed contribution analysis revealed that the better environmental performance of the beach well intake plant was significantly influenced by its comparatively low electricity use in the simplified pre-treatment process. The better economic performance of the plant with beach well intake was mostly due to savings in chemical use. The results are based on site specific assumptions. However, the LCA and LC framework developed herein could be used to determine the optimum SWRO seawater intake and pre-treatment configuration at plant sites with different characteristics to those modelled herein, provided sufficient data is available.

1. Introduction

Reliable water supply systems are crucial elements of urban infrastructure, and planning their expansion is challenging. The threat of climate change and global population growth has cast doubt upon the sustainability of traditional water supply sources. This has led to a shift away from reliance on traditional climate dependant supplies such as groundwater and surface catchment dams towards a combination of novel technologies, integrated water sources, water reuse and seawater desalination to provide water security for future urban areas. Seawater desalination provides high quality water. Approximately three billion people — about half of the world's population — live within 200 km of a coastline [1] and 97% of all the water on the planet is saline, so seawater is an accessible resource. Currently, reverse osmosis (RO) is the leading technology for desalination [2]. However, there are concerns over its high cost and environmental impacts when compared to traditional water sources.

Life cycle assessment (LCA) has been utilised to explore strategies for reducing the environmental impacts of RO processes, such as moving towards renewable energy inputs [3–8], cleaner fossil fuels [9,10] and plants' size and location optimization [11]. Muñoz and Fernández-Alba [12] quantified the environmental performance improvement that could be obtained by extracting low salinity groundwater instead of seawater for an RO process. Hancock et al. [13] investigated the improvement in environmental performance of coupled seawater desalination and water reclamation by application of new hybrid technologies. The environmental impacts of seawater reverse osmosis (SWRO) with alternative pre-treatment facilities of ultra filtration (UF) and granular media filter have been also reported [14–16]. However, to the authors' best knowledge, the comparative environmental

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performance of extracting high quality seawater using subsurface intakes for SWRO has not been previously quantified.

Intake facilities extract and provide feedwater for desalination plants. There are two main categories of intake, namely surface intakes and subsurface intakes. Surface intakes collect seawater directly from the ocean and deliver seawater to desalination plants while subsurface intakes tap into the saline coastal aquifer under the ocean floor, onshore or off-shore [17]. The quality of seawater extracted from the subsurface is very site specific. There are sites in which seawater extracted via subsurface filtrates naturally through the seabed, and compared to an open intake extraction, the use of the technology at these sites usually results much lower solids, silt, oil and grease, natural organic contamination, and aquatic micro-organisms [18] in the feedwater which leads to simplification of pre-treatment prior to RO and less chemical consumption for membrane cleaning [17,19–21]. For example, in Malta and the Caribbean there are numerous subsurface intake technology-based SWRO plants which only use bag filters or cartridge filters ahead of their SWRO membrane systems. This minimal level of pre-treatment is feasible when subsurface intakes are located in a well flushed ocean bottom or shore, away from surface fresh water influence, with seawater collected from a coastal aquifer of uniformly porous structure such as limestone [17]. Without the appropriate site specific conditions, subsurface intake technology could be a costly choice. Factors such as low productivity of the seashore, low subsurface water quality, high concentration of iron or/and manganese or CO_2 in feedwater, high variation of source water quality and temperature, and polluted subsurface intake water under influence of contaminated groundwater all present challenges for SWRO projects with subsurface intakes [19,22]. Thus, to avoid ineffective employment of the technology, site-specific feasibility assessment is essential prior to plant construction [19].

The most common type of subsurface intake for SWRO desalination plants is beach well intake [18,19]. However, there are a number of factors restricting beach well technology as the intake choice for large plants. First, the modular configuration of beach well intake facilities does not deliver the economies of scale enjoyed by open intake facilities [19], making beach well intakes a cost competitive choice only for smaller plants [18]. Second, open intake technology is a better option than beach well technology for large plants due to the limited source water capacity of beach wells [2]. For large plants there is a need for a large number of constructed wells which could disturb a significant area of seashore land and natural habitat, because wells are typically located on seashore within 100 m of the ocean [18]. Despite these technical and economic constraints, previous literature [19] has reported that at numerous sites the environmental performance of beach well intake plants was superior to open intake fed plants due to lower chemical and electricity use in the pre-treatment phase, although these advantages were not quantified.

This paper quantifies the environmental and economic performances of a SWRO plant using beach well intakes under favourable hydro-geological conditions and compares the results to those obtained for an open intake plant. Comparative LCA and levelised cost (LC) estimates are made for two SWRO process configurations, these being one *open intake scenario* and one *beach well scenario*. For the *open intake scenario* we focus on a 35,000 m^3/day design capacity SWRO desalination plant with an open intake and membrane pre-treatment prior to RO. For the *beach well scenario*, we again focus on a plant with design capacity of 35,000 m^3/day, but in which feedwater was extracted from the subsurface using beach well intake and filtered by only a cartridge filter prior to RO. Although the results are based on site-specific assumptions, the analytical framework detailed below could be readily adapted to assess the comparative environmental and economic performances of SWRO intake/pre-treatment configurations at other sites, such as those with less favourable hydro-geological conditions.

2. Methodology

2.1. Life cycle assessment

The LCA method applied the ISO14040 [23] standard, with the LCA conducted in four stages: goal and scope, life cycle inventory (LCI), life cycle impact assessment, and interpretation. Uncertainty analysis was conducted to assess the influence of variations in process data and model choices on the results. The software SimaPro [24] with connected databases as described in the following sections was used for all LCA modelling and uncertainty analysis.

2.1.1. Goal and scope

The goal of this LCA was to quantify and compare the life cycle impacts of the *open intake scenario* and the *beach well scenario*. The input and output flows of the SWRO plants were determined by conceptual design and site data. The scope of this study was primarily cradle to gate. The LCA covered the construction and operational phase of both SWRO configurations. The main flows in the operational phase were chemical use, consisting of clean in place (CIP) and chemical enhanced backwash (CEB) processes, materials consumed for membrane replacement, and electricity consumption associated with seawater extraction, disc filter (DF), cartridge filter (CF) ultra-filtration (UF) and RO. Disposal of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged brine to sea was also covered. The same functional unit (1 m^3 of desalinated water) was chosen for both scenarios to make them comparable. A time boundary of 30 years was selected for both scenarios. The scenarios' system boundaries and input flows are illustrated in Fig. 1.

2.1.2. Life cycle inventory

LCI analysis is a key step in LCA, involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle [23]. Suh and Huppes [25] identify three main categories of LCI method: process-LCI; economic input–output (EIO)-LCI, and hybrid-LCI. Process-LCI tracks the material and energy flows into the system at the process engineering level and is highly detailed, but suffers from onerous data requirements that make the modelling of complete systems impossible. EIO-LCI quantifies environmental impacts across economic sectors and is able to model a complete economic system using publicly available data, but lacks engineering detail. In general terms, a hybrid-LCI links together a process-LCI and an EIO-LCI in a manner that removes the weaknesses of each approach while retaining their strengths [25].

In this study, SWRO plant construction phase impacts were accounted with EIO-LCI and operational phase impacts were accounted with process-LCI.

2.1.2.1. Desalination plant construction phase: EIO-LCI. An EIO-LCI model augments a country's economic input–output matrix [26] with a matrix of ecological output of each economy sector to obtain a supply chain of product environmental data. In EIO-LCI, the final inventory vector can be calculated by the following mathematical model [27]:

$$Q = N \cdot X^{-1} \tag{1}$$

$$A = Z \cdot X^{-1} \tag{2}$$

$$E = Q \cdot (I - A)^{-1} f, \tag{3}$$

where $N = [n_{kj}]$ is a matrix of ecological commodity output, n_{kj} indicates the amount of ecological commodity output k associated with the output of economy sector j in physical units, $X = \mathrm{diag}[x_i]$ is a matrix of "Total Output", x_i indicates the total industry output summation of output consumed by intermediate industries, final users and exports, X is a

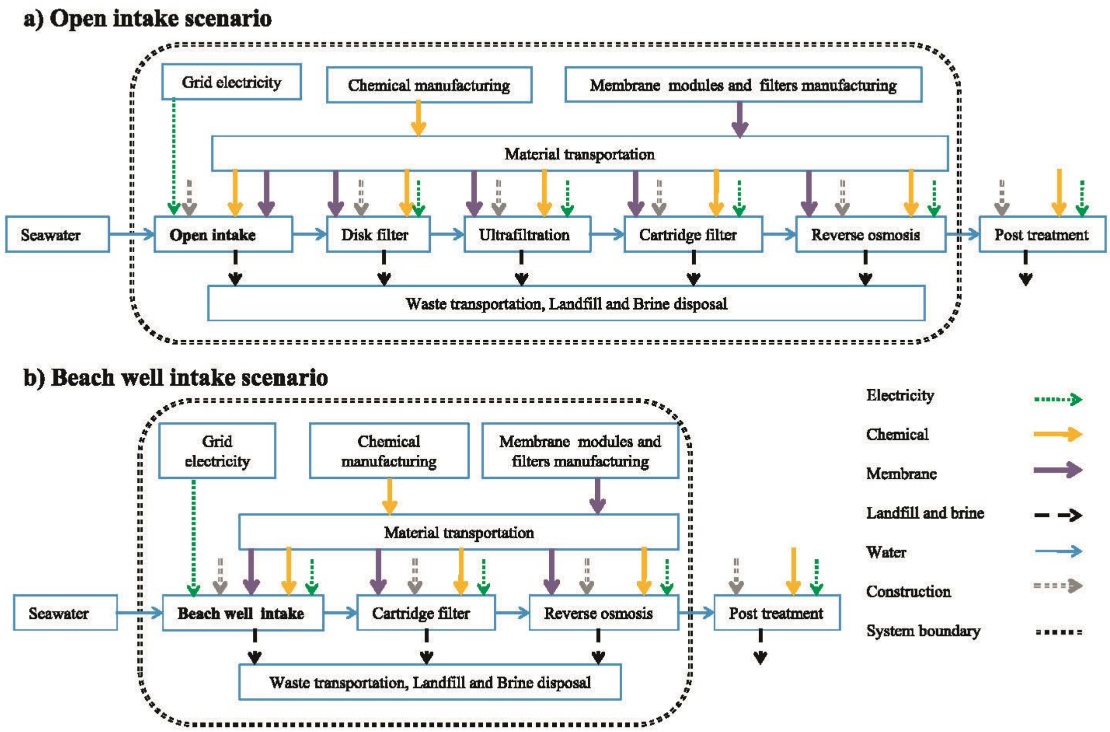

Fig. 1. Graphical overview of the system boundaries and input flows for the SWRO desalination plants, (a) *open intake scenario* and (b) beach well intake scenario.

diagonal matrix with the elements of the vector $x = [x_i]$ strung out along its main diagonal, $Z = [z_{ij}]$ is a matrix of interindustry transactions, z_{ij} indicates the amount of output from industry sector i used by industry sector j in monetary unit, I is an identity matrix, $f = [f_i]$ is a vector of final demand, and $E = [e_{ij}]$ is an LCI matrix where e_{ij} reflects the amount of ecologic output i directly and indirectly associated with delivering a dollar's worth of industry j output to final demand.

In using EIO-LCI, monetary flows are used instead of mass or energy flows as foreground data. The prices (excluding taxes) of components, materials and services need to be obtained for the year in which the country's economic input–output matrix data were collected. The time it takes for national statistics agencies to compile input–output data means that it is normally three to four years old before it can be used for an EIO-LCA. As such, an assumption must be made that the input–output structure of the economy remains stable over the intervening period. In the current study background data was obtained from USA Input output 2002 database for non-residential manufacturing structures sector in SimaPro software [24]. This assumed geographical correlation between Australia and the USA is based on Ecoinvent's suggestion that in the case of the lack of LCI data for Australia, North America databases could be considered as a replacement because of the countries' similarities in environmental legislations. Construction phase costs were obtained as described in Section 2.2 below and converted to 2002 US$ to be in compliance with USA input–output 2002 database.

2.1.2.2. Desalination plant operational phase: process-LCI. Primary LCI data for electricity, membrane, landfill and brine were generated for two conceptual plant designs using ROSA [28] and ERI [29] software (Fig. 1) for RO processes, manufacturer data, hydraulic calculations for extraction and pre-treatment processes and mass balance equations for landfill and brine flows. In the *open intake scenario*, chemical use was based on a SWRO desalination plant with an open intake for feedwater extraction and membrane filtration for pre-treatment located in Perth, WA [4]. In the *beach well scenario*, chemical use data was obtained through personal communication [30] for a desalination plant in Milos Island, Greece [31] which uses a beach well intake for seawater extraction and a cartridge filter prior to RO. The LCIs for both scenarios' operational phases are provided in Table 1.

LCI background data were obtained from SimaPro databases as follows:

- Electricity production model: Australian high voltage electricity data [32] was used for modelling onsite energy consumption. Grid mix electricity supply and also transmission losses were included in the database.
- Chemical manufacturing: Sugar manufacture was used instead of citric acid. Alkylbenzene sulfonate was used instead of detergent. Sodium tripolyphosphate manufacture was used instead of scale inhibitor. Other chemicals were directly selected from the Ecoinvent [33] or Australasian database [32].
- Membrane manufacturing: The processes selected for membrane manufacturing included membrane material production plus extrusion and injection moulding. All process data were obtained from Ecoinvent [33] or Australasian database [32].
- Transportation: In both scenarios, transportation distances for chemicals, waste and membranes were assumed to be the same as material transportation for a desalination plant in Perth, WA and obtained from published document [4]. A twenty tonne articulated truck was selected as the transport vehicle for transportation within Australia [32].

Table 1
Life cycle inventory for both scenarios' operational phases.

Subsystems	Input and output flows		Design assumptions
	Open intake scenario	Beach well scenario	
Seawater extracted per functional unit (1 m^3 of desalinated water)	2.27 m^3/m^3	2.02 m^3/m^3	Assumptions included a plant design capacity of 35,000 (m^3/day), annual plant capacity factor of 0.85, and annual production of 10.9×10^6 (m^3). Recovery ratios were assumed to be 99% for the DF and the CF. The UF recovery ratio was assumed to be 90%. The RO recovery ratio was assumed to be 50%. Feed water quality for designing RO trains is based on Indian Ocean seawater quality [20]; TDS = 40,000 mg/l, temperature = 30 °C. The largest common size for beach well intake plants is selected as plant design capacity.
Electricity use per functional unit (1 m^3 of desalinated water)			
Extraction	Open intake (0.05 kWh/m^3).	Beach well (0.16 kWh/m^3).	For the *open intake scenario*, electricity use was calculated for a single open ocean intake. A 500 m distance between plant and ocean was assumed. Head loss due to friction was assumed to be 3 m/km. The open intake has one duty variable-speed pump and one standby variable-speed pump with efficiencies of 94% and electric motor efficiencies of 82%. For the *beach well scenario*, electricity use was calculated for five wells with 20 m depth. Five duty wells with daily yield of 15,000 m^3/day per well and one standby well were considered. Each well was assumed to be equipped with one variable-speed, 94% efficiency pump and electric motor efficiency of 82%.
Pre-treatment	Disc filter (DF), UF, cartridge filter (CF) (0.28 kWh/m^3)	CF (0.02 kWh/m^3)	Average pressure drop during operation was assumed to be 0.3 bar for the CF and 0.22 bar for the DF. The UF recovery ratio was assumed to have 3 bar maximum transmembrane pressure. In both scenarios, pumps with an efficiency of 94% and electric motor efficiency of 82% were assumed for UF, DF and CF.
RO	Single pass RO with recovery ratio of 50% (2.85 kWh/m^3)	Single pass RO with recovery ratio of 50% (2.85 kWh/m^3)	Single pass RO is the most common practice for SWRO. The RO designed using ROSA software and ERI model [28,29]. Each pressure vessel in the RO system was assumed to contain eight membrane elements connected in series. Both plants were assumed to have 6 RO trains.
Chemical use per functional unit (1 m^3 of desalinated water)			
Extraction and pre-treatment	Intermittent chlorination (sodium hypochlorite; 1.94 g/m^3), acid rating (sulphuric acid; 0.69 g/m^3), oxidants scavengers (sodium metabisulphite; 0. 07 g/m^3), CEB (citric acid; 0.28 g/m^3, sodium hypochlorite; 1.63 g/m^3) and trace amounts other chemicals.	Scale inhibitor; 2 g/m^3.	For the *open intake scenario*, the dosing rate for a desalination plant in Perth, Australia was adopted [4]. The *beach well scenario* used the dosing rate of the Milos desalination plants in Greece [31], which was obtained through personal communication [30].
RO	CIP (citric acid; 0.65 g/m^3, detergent; 2.72 g/m^3, caustic soda; 0.4 g/m^3, biocide; 9.86 g/m3).	CIP (citric acid; 0.15 g/m^3, detergent; 1.53 g/m^3, caustic soda; 0.15 g/m^3).	As above.
Membrane use per functional unit	PP; 0.05 g/m^3, PE; 0.50 g/m^3, PU; 0.14 g/m^3, ABS; 1.27 g/m^3, PA; 0.14 g/m^3.	PE; 0.48 g/m^3, PU; 0.08 g/m^3, ABS; 0.68 g/m^3, PA; 0.14 g/m3.	Polypropylene (PP) is assumed for the production of UF fibre and polyamide (PA) for RO fibre. Polyethylene (PE) was selected for RO and UF protective mesh, acrylonitrile–butadiene–styrene (ABS) for membrane casing and polyurethane (PU) for gluing the elements. The weights of the RO and UF modules were obtained from the manufacturers' data. The weight fraction of these materials in each RO and UF module was adapted from [34] and the authors' engineering judgement. The useful life of the RO and UF membranes was assumed to be 5 years [17].
Landfill and brine	Brine; 1.27 m^3/m^3, disposed membrane to plastic landfill; 2.11 g/m^3.	Brine; 1.01 m^3/m^3, disposed membrane to plastic landfill; 1.38 g/m^3.	In both scenarios brine has TDS of 80,000 mg/L.

2.1.3. Life cycle impact assessment and uncertainty analysis

Life cycle impact assessment (LCIA) is the final phase of LCA in which inventory data is converted into impact results through the use of appropriate algorithms or indicators of environmental burdens, aimed at simplified understanding and assessment of the environmental impact of the product system [35]. Based on ISO 14044 [36], LCIA consists of obligatory elements of classification and characterisation and optional elements of normalisation, ranking, grouping and weighting. In this study the characterisation is based on the CML 2001 method [37] which provides ten obligatory impact indicators at a midpoint level. These impact indicators include: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion (ODP), human toxicity potential (HTP), fresh water aquatic eco-toxicity (FWAE), marine aquatic eco-toxicity potential (MAETP), terrestrial eco-toxicity potential (TETP) and photochemical oxidation potential (POCP).

In this study, Monte Carlo simulation was employed for uncertainty analysis facilitated by an algorithm in the SimaPro software [24]. A pedigree matrix was employed for accounting the material and energy flows uncertainty based on the method documented in the Ecoinvent methodology report [38]. The assigned uncertainty factors of data reliability, completeness, temporal correlation, geographical correlation, technological correlation and sample size are listed in supplementary document Table S1.

2.2. Levelised cost

LC is an engineering economics metric that is used for measuring and comparing the costs of alternative projects that deliver similar products. It is the real price at which a long term contract would need to be negotiated in order for a project to breakeven in net present value (NPV) terms. We partition LC into two components, levelised capital cost (LCC) and levelised operational cost (LOC), such that

$$LC = LCC + LOC. \tag{4}$$

LCC is given by

$$LCC = \frac{\sum_{t=0}^{n} \frac{K_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}}, \tag{5}$$

where K_t denotes the capital cost (capex) accruing in year t ($), Q_t water production in year t (m^3), r the weighted average cost of capital (WACC) — i.e. the rate of return required to service the combined costs of equity and debt — and n the amortisation period.

LOC is given by

$$LOC = \frac{\sum_{t=0}^{n} \frac{V_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}}, \tag{6}$$

Where V_t denotes the operational cost (opex) accruing in year t ($). All capital and O&M costs except electricity, land and labour for both scenarios were adopted from the literature [39] and were adjusted to 2013 Australian dollars (AU$) using exchange rates obtained from Reserve Bank of Australia database [40] and producer price indices obtained from Australian Bureau of Statistics database [41]. Land requirements in hectares were obtained from [39] and the unit cost of land was assumed to beAU$300/$m^2$. The amount of electricity use was based on conceptual design (Section 2.1.1) and the wholesale electricity price of AU$143 per MWh was obtained from the literature [42]. The number of full time staff required for routine maintenance and operation was adapted from [39]. Labour cost was calculated based on a 2013 labour rate of AU$68,203 per year. The real WACC of 6.62% proposed by the Western Australian Water Corporation was selected for the LC analysis [43].

3. Results and discussion

3.1. LCA results

3.1.1. Contribution analysis

Identifying the key materials and processes with dominant environmental impacts during the life cycle of the system has a significant role in the interpretation phase of LCA [36]. In this study contribution analysis is conducted for six subsystems:

1. Electricity use in the treatment process
2. Membrane material use in the pre-treatment and RO processes, including material manufacturing and transportation
3. Chemical use in the treatment process, including chemical manufacturing and transportation
4. Landfill of disposed membrane
5. Brine disposal
6. Construction of buildings and facilities.

As shown in Fig. 2, the LCA results for membrane, landfill and brine disposal indicate that in combination they contributed less than 3% of total environmental impacts in both scenarios across all impact categories. In both scenarios, electricity use in the operational phase contributed more than 75% of the total impacts across all impact categories, with the exception of ODP (~23 to ~26%) where the construction phase was the dominant impact contributor (65% for the *open intake scenario* and 71% for the *beach well scenario*). Otherwise, the contribution of plant construction to total environmental impact was relatively small (less than 4% of the total impact), with the exception of the TETP indicator (17% for TETP in the *open intake scenario* and 22% for TETP in the *beach well scenario*).

To further identify the differences in both scenarios supply chain, a detailed contribution analysis was conducted at the substance and process level as illustrated in supplementary document, Table S3. These detailed contribution analysis results combined with the process network used for comparing the LCAs of the two scenarios are presented in Table 2.

Zhou et al. [9] conducted a similar, detailed contribution analysis for RO processes with different electricity production models in the United States (US), Spain and Singapore. Comparing results from our study with that previous study revealed that in Spain, the major processes were associated with natural gas and coal burning, which is similar to our results. In the US, producing electricity from hard coal had the highest contribution amongst all impact categories while in Singapore,

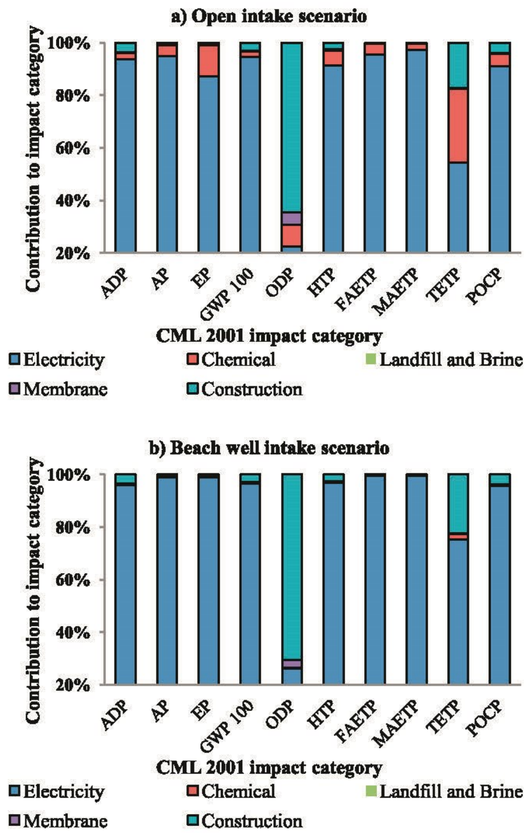

Fig. 2. Contribution analysis of subsystems to the life cycle impacts, *open intake scenario* (a) and beach well intake scenario (b).

Table 2
Main contributors associated with the life cycle impacts of SWRO and benefit of beach well intake over open intake.

Impact categories	Main contributors in supply chain	Benefit of beach well intake over open intake
ADP	70% is associated with extraction of black coal and lignite for generating electricity for use in chemical manufacturing and onsite electricity use in SWRO plants.	Less onsite electricity and chemical use in operational phase
AP and EP	87–90% of AP and 73–83% of EP are associated with electricity generation process from black and brown coal fuels, mostly due to the by-product combustion of nitrogen oxides and sulphur oxides in coal fired power plants.	Less onsite electricity and chemical use in operational phase
GWP	Greenhouse gas emission emitted from the combustion of black and brown coals in coal fired power plants accounts around 75% of the overall contribution.	Less onsite electricity use in operational phase
ODP	The electricity generation process from natural gas power plants accounts for more than 40% of the overall contribution and construction phase (e.g. lighting fixture and machinery manufacturing) accounts for 30% contribution in life cycle impacts.	Less onsite electricity use in operational phase and less construction phase impacts due to simplification in pre-treatment facilities
HTP, FAETP and MAETP	75–80% of HTP, 94–98% of FAETP and MAETP are associated with disposal of hard coal ash to water for electricity production in coal fired power plants.	Less onsite electricity and chemical use in operational phase
TETP	41–57% of TETP is associated with electricity generation process from coal fuels. Emissions of nickel to soil and mercury to air are responsible for more than 50% of TETP. Construction phase (e.g. cement manufacturing, alumina refining and production, and waste management) accounts for 17–20% contribution in life cycle impacts.	Less onsite electricity and chemical use and less construction phase impacts due to simplification in pre-treatment facilities
POCP	Emission of sulphur oxides and carbon monoxide to air for electricity production in coal fired power plants accounts for more than 74–78% contribution.	Less onsite electricity use and chemical in operational phase

heavy fuel oil burning was the major sub-process responsible for environmental impacts [9].

In summary the contribution analysis revealed that the environmental impacts of the full SWRO supply chain were mainly associated with the emission intensities of the electricity production model. This implies that, by substituting an open intake with beach well intake at suitable sites, life cycle environmental impacts can be reduced as a result of less electricity use in SWRO plant onsite, in upstream chemical manufacturing and in upstream material production for infrastructure construction.

3.1.2. Scenario comparison and uncertainty analysis

Fig. 3 shows the normalised impacts of the two scenarios across the ten impact categories. Each scenario is normalised by the maximum value observed between the two scenarios, so the scenario with the largest environmental impact in each category is normalised as 100%. The absolute values of characterisation results for all impact categories are illustrated in supplementary document, Table S4.

Overall, the results of the LCA indicate that all environmental indicators associated with SWRO can be reduced significantly if seawater is extracted through beach well intake instead of open intake facilities. Environmental burden reduction of ~10% was observed in ADP, AP, GWP, MAETP and POCP indicators. These are the indicators which are mostly affected by electricity use in the operational phase. However reductions of up to 31% were observed for the EP, HTP, FEATP, ODP and TETP indicators. This is because these indicators are significantly influenced by chemical use in the operational phase.

Uncertainty analysis was conducted to assess the influence of variations in process data and assumptions on the results of comparative LCIA. Fig. 4 shows Monte-Carlo simulation results with a 95% confidence interval for 1000 runs. The percentages illustrate the estimated probability of one scenario achieving a lower impact than the other. The *beach well scenario* had lower environmental burdens across all impact categories for 57–93% of the runs.

3.1.3. Sensitivity of the environmental benefits to energy source

The Australian electricity mix was chosen to model the onsite electricity use and electricity use for material manufacturing in the LCA analysis as described in Section 2.1.2.2. The Australian energy mix consists of approximately 70% coal, 14% natural gas and the remaining 7% is derived from several sources including wind and photovoltaic. In order to investigate the environmental impact sensitivity of the electricity mix assumption, two other electricity mix scenarios were modelled: USA

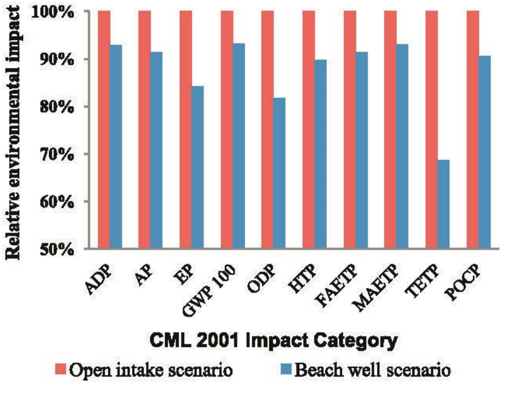

Fig. 3. Relative environmental impact of *open intake scenario* and *beach well scenario*, with each scenario normalised by the maximum impact value observed across the two scenarios.

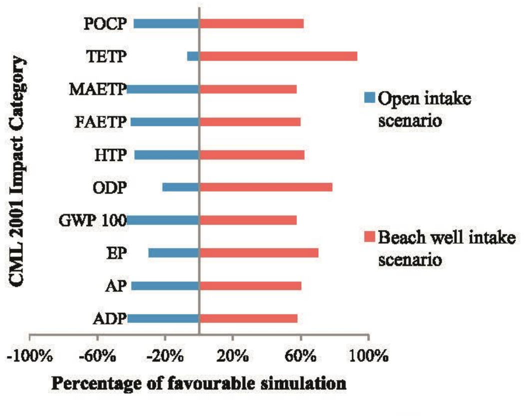

Fig. 4. Uncertainty analysis results (Monte Carlo simulation with a 95% confidence interval, run 1000 times).

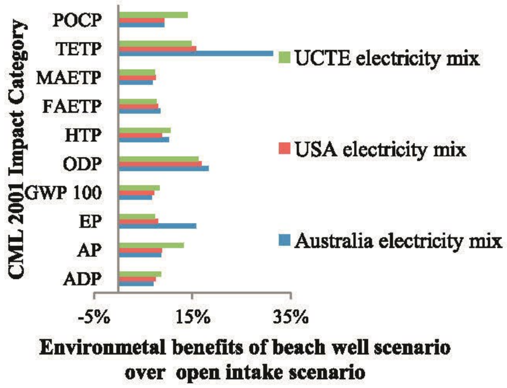

Fig. 5. Benefits of beach well intake scenario over *open intake scenario* in percentage terms for three different electricity mixes.

and Union for the Co-ordination of Transmission Energy (UCTE). Differences between normalised impacts of the two scenarios under three different electricity production models across the ten impact categories are presented in Fig. 5. Results suggest that an improved environmental performance may be obtained through the use of the beach well intake configuration in lieu of the open intake configuration under all three energy models. The AP, EP, ODP, TETP, and POCP indicators were more sensitive to changes in the energy production model in than the ADP, GWP, HTP, FATP, and MAETP indicators. The improved environmental performances of the beach well configuration relative to the open intake configuration ranged between 7% and 31% across all environmental indicators and energy production models.

3.2. Economic assessment

The LC of produced water was used as an indicator of financial performance. Table 3 partitions LC into LCC and LOC sub-categories. For each scenario capex comprises construction, overhead, land and annual membrane replacement costs, while opex comprises all operational and maintenance costs, over a period of 30 years. A more detailed breakdown of the scenarios' construction costs is provided in the supplementary document, Table S5.

The LC results range between 2.20 and 2.52 AU$/m^3 across the two scenarios. The *open intake scenario* has a 13% higher LC than the *beach well scenario*. Moreover, the *open intake scenario* has a higher LCC and LOC than the *beach well scenario*. However, the difference in LC across the scenarios is mostly influenced by LOC. The lower LOC in the *beach well scenario* is due to its lower operational chemical and electricity requirements: a result of the higher quality water extracted from its beach well intake. Contribution analysis shows that LOC is comprised mainly of electricity costs followed by chemical costs in the *open intake scenario* and labour cost in the *beach well scenario*.

3.3. Future studies

Given that the defined *beach well scenario* process configuration is based upon the Milos Island desalination plant in Greece [31] the configuration we have modelled is likely to be feasible at comparable sites around the globe. However, subsurface feedwater at some sites may have less favourable characteristics than that modelled, such as high concentrations of manganese and/or iron, low dissolved oxygen concentration, low temperature, high CO_2 concentration, MTBE contamination and also the possibility of salinity change over time. Quantification of the environmental and economic performance of SWRO using subsurface intake under these more challenging conditions deserves further research.

The current study focuses only on emissions to air, land and water associated with the supply chain of the SWRO desalination process using the CML2001 characterisation method for LCIA. The method applied herein can assist in the development of mitigation strategies targeting those parts of the SWRO supply chain responsible for the largest environmental impact contributions. However, there are other potential environmental impact categories that may be affected by the employment of beach well or other types of subsurface intakes, for example, marine life (impingement and entrainment) and infrastructure construction impacts (noise impacts associated with drilling wells offshore or onshore). Future models would benefit from the inclusion and quantification of such impact categories in the LCA.

Finally, the augmented EIO-LCA method (the top-down approach) was used in the current study to account for the impacts of the SWRO construction phase, during which the ODP and TETP indicators were found to be significant. It is recommended that a detailed and comprehensive process-LCI be developed for the construction phase of desalination plants to help decision makers find possible onsite strategies for reducing these impacts, particularly for subsurface intake construction work such as drilling wells offshore or onshore.

4. Conclusion

Under favourable hydro-geological conditions, SWRO plants combining a beach well intake with simplified pre-treatment prior to RO can significantly reduce the environmental impacts of the system at a lower economic cost per unit of desalinated water when compared to a typical open intake and membrane pre-treatment SWRO plant configuration. Detailed contribution analysis indicates that the better environmental performance of the plant with beach well intake is significantly influenced by lower electricity use in its simplified pre-treatment

Table 3
Cost breakdown of each scenario for functional unit of 1 m^3 water of desalinated water.

Levelised cost of activities	Open intake scenario		Beach well scenario	
	LC (AU$/m^3)	Activities contribution	LC (AU$/m^3)	Activities contribution
Building and facilities' construction (capex)	1.464	58%	1.326	60%
Overhead cost (capex)	0.162	6%	0.147	7%
Land cost (capex)	0.011	0%	0.008	0%
Membrane replacement (opex)	0.068	3%	0.068	3%
Energy use in treatment (opex)	0.461	18%	0.432	20%
Labour cost (opex)	0.083	3%	0.083	4%
Chemical use (opex)	0.168	7%	0.032	1%
Replacement parts and maintenance (opex)	0.068	3%	0.068	3%
Insurance (opex)	0.040	2%	0.036	2%
LCC (total capex)	1.705	68%	1.549	70%
LOC (total opex)	0.819	32%	0.651	30%
LC (total cost)	2.524	100%	2.200	100%

process compared to that required for the membrane pre-treatment process. Moreover, the results suggest that substituting an open intake configuration with a beach well intake configuration can lead to less electricity input requirements throughout the SWRO supply chain (chemical manufacturing, material production and onsite energy use) and therefore a lower environmental impact. Furthermore, LC modelling suggests that this improved environmental performance can be achieved at a lower economic cost, mainly due to savings in chemical use through the employment of the beach well intake configuration. All of these results are based on site specific assumptions. However, the LCA and LC framework developed herein could be used to determine the optimum SWRO seawater intake and pre-treatment configuration at plant sites with different characteristics to those modelled herein, provided sufficient data is available.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2014.12.003.

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3.3. Chapter summary and link to the next chapter

This chapter addresses the second research question, namely, **what are the influences of feedwater extraction technology on the life cycle environmental performances of a Seawater Reverse Osmosis (SWRO) desalination supply chain**. A comparative Life Cycle Assessment (LCA) and Levelised Cost (LC) of two scenarios were carried out: an open intake scenario in which a Seawater Reverse Osmosis (SWRO) desalination plant employs open intake and membrane pre-treatment prior to Reverse Osmosis (RO), and a beach well scenario in which feedwater is extracted from the subsurface using beach well intake and cartridge filter prior to RO. Results showed that under favourable hydro-geological conditions, SWRO plants combining a beach well intake with simplified pre-treatment prior to RO can significantly reduce the environmental impacts of the system at a lower economic cost per unit of desalinated water when compared to a typical open intake and membrane pre-treatment SWRO plant configuration. The key contribution of the study in the field is raising the awareness about possible environmental and economic benefits associated with employing beach well intake in SWRO plants. Given that feedwater extraction technology has significant influence on the life cycle environmental performance of desalination plants supply chain, this decision is incorporated as a key decision variable in desalination supply chain decision model developed in chapter 6. Moreover, the results of this chapter use as input data to the model in chapter 6.

3.4. Appendix A: Paper 2 Supporting information

Table S1 Uncertainty factors contributing to the square of the geometric standard deviation obtained based on Ecoinvent methodology and published update uncertainty factors for the pedigree matrix [56, 57]

	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Open intake scenario					
Membrane materials (Pre-treatment)	1.61	1.00	1.00	1.00	1.00
Membrane material (RO)	1.61	1.00	1.00	1.00	1.00
Chemical use (intake & Pre-treatment)	1.00	1.00	1.03	1.00	1.00
Chemical Use (RO)	1.00	1.00	1.03	1.00	1.00
Plastic waste	1.61	1.00	1.00	1.00	1.00
Construction	1.54	1.00	1.19	1.04	1.00
Electricity (Intake)	1.61	1.00	1.00	1.00	1.00
Electricity (Pre-treatment)	1.61	1.00	1.00	1.00	1.00
Electricity (RO)	1.61	1.00	1.00	1.00	1.00
Material Transportation	1.00	1.00	1.00	1.00	1.00
Beach well scenario					
Membrane materials (Pre-treatment)	1.61	1.00	1.00	1.00	1.00
Membrane material (RO)	1.61	1.00	1.00	1.00	1.00
Chemical use (intake & Pre-treatment)	1.54	1.00	1.00	1.00	1.00
Chemical Use (RO)	1.54	1.00	1.00	1.00	1.00
Plastic waste	1.61	1.00	1.00	1.00	1.00
Construction	1.54	1.00	1.19	1.04	1.00
Electricity (Intake)	1.61	1.00	1.00	1.00	1.00
Electricity (Pre-treatment)	1.61	1.00	1.00	1.00	1.00
Electricity (RO)	1.61	1.00	1.00	1.00	1.00
Material Transportation	1.00	1.00	1.00	1.00	1.00

Table S2 Square of the geometric standard deviation for uncertainty analysis obtained based on Ecoinvent methodology [56]

	Open intake scenario	Beach well scenario
Membrane materials (Pre-treatment)	1.61	1.61
Membrane material (RO)	1.61	1.61
Chemical use (intake & Pre-treatment)	1.03	1.54
Chemical use (RO)	1.03	1.54
Plastic waste	1.61	1.61
Construction	1.60	1.60
Electricity (Intake)	1.61	1.61
Electricity (Pre-treatment)	1.61	1.61
Electricity (RO)	1.61	1.61
Material Transportation	1.00	1.00

Table S3 Contribution analysis to the process and substance levels with cut off[1] criteria of 5%

	Open intake scenario (%)	**Beach well scenario (%)**
Abiotic deplation:		
Process		
Remaining processes	17	15
Black coal, at mine	42.8	43.8
Lignite	30.7	31.4
Natural gas, at natural gas separation plant/AU U	9.6	9.81
Substance		
Remaining substances	10	8
Coal	80	82
Gas, natural, 36.6 MJ per m3, in ground	10	10
Acidification:		
Process		
Remaining processes	13	10
Electricity, black and brown coal, at power plant	87	90
Substance		
Remaining substances	4	3
Nitrogen oxides	20	20
Sulfur oxides	76	77
Eutrophication:		
Process		
Remaining processes	27	17
Electricity, black and brown coal, at power plant	73	83
Disposal, hard coal ash from stove to sanitary landfill	7.8	8.8

[1] The processes and substances whose contribution is less than 5% of the total environmental load are presented here as remaining processes and remaining substances respectively.

	Open intake scenario (%)	Beach well scenario (%)
Substance		
Remaining substances	6	2
Nitrogen oxides	77	87
Phosphate	9	2
Chemical oxygen demand	8	9
Global warming potential :		
Process		
Remaining processes	26	24
Electricity, black and brown coal, at power plant	74	76
Substance		
Remaining substances	8	6
Carbon dioxide, fossil	92	94
Ozone layer depletion:		
Process		
Remaining processes	51	45
Electricity, natural gas, at power plant	20	23
Lighting fixture manufacturing SE	14	16
Other general purpose machinery manufacturing SE	15	16
Substance		
Remaining substances	40	32
Ethane, 1,1,1-trichloro-, HCFC-140	33	37
Methane, bromochlorodifluoro-, Halon 1211	20	23
Methane, tetrachloro, CFC-10	7	8
Human toxicity:		
Process		
Remaining processes	24	20
Disposal, hard coal ash from stove to sanitary landfill	76	80
Substance		
Remaining substances	54	30
Barium	22	23
Vanadium,ion	6	7
Thallium	38	40
Fresh water aquatic eco toxicity:		
Process		
Remaining processes	6	2
Disposal, hard coal ash from stove to sanitary landfill	94	98
Substance		
Remaining substances	12	13
Barium	10	10
Beryllium	40	40
Nickel, ion	16	14
Vanadium, ion	22	23
Marine aquatic eco toxicity**:**		
Process		
Remaining processes	4	2
Disposal, hard coal ash from stove to sanitary landfill	96	98
Substance		
Remaining substances	9	9

	Open intake scenario (%)	Beach well scenario (%)
Barium	11	11
Beryllium	73	73
Vanadium, ion	7	7
Terrestrial eco toxicity:		
Process		
Remaining processes	59	43
Electricity, black and brown coal, at power plant	41	57
Substance		
Remaining substances	51	45
Mercury	44	48
Nickel	5	7
Photochemical oxidation		
Process		
Remaining processes	26	22
Electricity, black and brown coal, at power plant	74	78
Substance		
Remaining substances	14	10
Carbon monoxide	8	8
Sulfur oxides	78	82

Table S4 Absolute values of environmental impact categories

Impact category	Unit	Open intake scenario	Beach well scenario
Abiotic depletion	kg Sb eq	0.022929	0.021301
Acidification	kg SO2 eq	0.01965	0.017957
Eutrophication	kg PO4--- eq	0.001291	0.001086
Global warming (GWP100)	kg CO2 eq	3.264958	3.043265
Ozone layer depletion (ODP)	kg CFC-11 eq	1.69E-07	1.38E-07
Human toxicity	kg 1,4-DB eq	0.915022	0.821548
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.743474	0.680104
Marine aquatic ecotoxicity	kg 1,4-DB eq	2368.825	2203.361
Terrestrial ecotoxicity	kg 1,4-DB eq	0.001634	0.001121
Photochemical oxidation	kg C2H4 eq	0.000763	0.000691

Table S5 Construction cost obtained from literature [58]

Investment cost in 2000 US$	Unit	Open intake scenario	Beach well scenario
Plant Daily Design Capacity	m^3/day	3.50E+04	3.50E+04
Plant Yearly production (0.85 plant capacity factor)	m^3/year	1.09E+07	1.09E+07
Plant Buildings Construction Cost	US$	4.40E+07	3.50E+07
Construction cost—concentrate disposal pipeline	US$	4.00E+05	4.00E+05

Investment cost in 2000 US$	Unit	Open intake scenario	Beach well scenario
Construction cost—surface water pretreatment	US$	6.50E+06	0.00E+00
Construction cost—open intake systems or wellfield	US$	2.20E+06	1.20E+07
Construction cost - seawater feed water pipeline	US$	8.00E+05	8.00E+05
Construction cost—site development	US$	1.50E+05	1.20E+05
Construction cost—post-treatment	US$	1.80E+06	1.80E+06
Construction cost—product storage using pre stressed concrete tank construction	US$	2.40E+06	2.40E+06
Construction cost – emergency generators	US$	7.00E+04	7.00E+04
Construction cost – step-down transformers	US$	3.80E+05	3.80E+05
Construction cost—membrane process buildings	US$	1.90E+06	1.90E+06
Freight and Insurance	US$	3.03E+06	2.74E+06
Interest During Construction	US$	2.73E+06	2.47E+06
Construction Overhead	US$	8.64E+06	7.82E+06
Owner's Direct Expense	US$	5.45E+06	4.94E+06
Contingency	US$	6.06E+06	5.49E+06
Working capital	US$	1.50E+05	1.50E+05

CHAPTER 4. QUANTIFY AND COMPARE THE GHG EMISSIONS OF CENTRALISED AND DECENTRALISED SWRO DESALINATION OPTIONS

4.1. Attribution

Maedeh P. Shahabi wrote all sections of this paper, carried out all LCA and LC modellings, designing conceptual scenarios and conducted all data analysis. Goen Ho acted as co-supervisor and advised on the scope of the study and scenario development. Martin Anda acted as principal supervisor and revised several drafts of the paper and gave feedbacks on the case study data and supply system design.

Maedeh P. Shahabi: +80%

4.2. Paper 3: Shahabi, Shahabi, M. P., Anda, M., & Ho, G. (2014). Influence of site-specific parameters on environmental impacts of desalination. Desalination and water treatment, 357, 259-266.

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Influence of site-specific parameters on environmental impacts of desalination

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ABSTRACT

Many metropolitan areas have a high dependency on Seawater Reverse Osmosis (SWRO) desalination plants for bulk water supply. Location and scale decisions are important for SWRO desalination plants owing to the significant environmental costs associated with long distance water pumping. The aim of this study is to introduce a Geographical Information System (GIS)-based method to assist such site-specific decisions. The method has 3 stages. Stage 1 uses GIS to identify feasible plant locations and water demand areas. Stage 2 develops a range of scenarios that balance plant size and number with water demand. In stage 3, the preferred scenario is selected based on environmental life cycle assessment. The method's applicability was tested using data for the northern corridor of Perth, Western Australia (WA). Spatial water demand and suitable vacant land for accommodating SWRO plants in the case study are obtained in Stage 1. Based on these spatial data, two water planning options are designed in order to supply desalinated water to the demand area. The first option consists of a large SWRO desalination plant and its connected trunk main which supplies water into the demand centrally (centralized scenario). Second option consists of five medium-sized SWRO desalination plants integrated within the demand area (distributed scenario). The best scenario for environmental performance was found to be the distributed scenario which has 18% less GHG emission compared to centralized scenario. This method is adaptable to other case studies for identifying optimal SWRO plant sizes and locations based on environmental criteria.

Keywords: Distributed water supply; GIS; Life cycle assessment; Perth; Reverse osmosis; Plant size

1. Introduction

Over the past decade, population growth and climate change necessitated a shift from relying on conventional water sources to a diversified climate change independent water resource such as seawater and wastewater. Moreover, seawater desalination allows access to unlimited source of ocean. However, high energy intensity and subsequently high environmental impacts of desalinated seawater gives rise to concerns on its sustainability.

Since the 1990s, life cycle assessment (LCA) has been used as a tool to account and improve environ-

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mental performance of seawater desalination [1]. LCA studies of different seawater desalination technologies showed that Reverse Osmosis (RO) process has lower environmental load in comparison with thermal technologies of Multi Effect Desalination and Multi Stage Flash due to lower primary energy use and higher energy efficiency [2]. Due to significant role of energy use in total life cycle environmental impacts of seawater reverse osmosis (SWRO), previous studies investigated the effect of different electricity production models on the life cycle airborne emissions associated with desalination technologies and concluded that the electricity production models with a higher share of renewable energy decreased the environmental impact of desalination [2–4].

Although life cycle environmental impacts of SWRO have been accounted in previous work [2–5], no investigation of the influence of site-specific parameters such as size and location of SWRO desalination plants on their environmental impacts has been made. In order to capture the influence of these parameters on their environmental performance, a Geographical Information System (GIS)-based methodology was developed to aid in such decision makings. Another contribution of this study is through comparing centralized and distributed desalinated water supply system for a case study of Perth, Western Australia (WA).

2. Materials and method

2.1. Case study—Perth, WA

The methodology as will be described in Section 2.2 is applied to a case study in the northern Perth metropolitan area, WA. Perth is currently the largest user of seawater desalination [6] among Australian cities. Half of the water supply for the Perth and surrounding area is sourced from two large SWRO plants. The Southern Seawater Desalination Plant and the Perth Seawater Desalination Plant contribute 100 and 45 GL per year, respectively. A new SWRO desalination plant is proposed to support future urban expansion in the northern corridor of Perth and to replace a loss of capacity in the groundwater system [7]. In this study five desalinated water demand areas are considered in northern corridor of Perth as illustrated in Fig. 1(A).

2.2. GIS-based model

A three-stage methodology to identify location and scale decisions for SWRO desalination plants is proposed. The three stages are (1) identify the demand areas and feasible plant locations (Stage 1), (2) develop a range of scenarios that balance plant size and number with water demand (Stage 2), and (3) selection of preferred scenario based on their environmental performance (Stage 3). All spatial related tasks are performed using ArcGIS version 10.

2.2.1. Stage 1

2.2.1.1. Site selection. Site selection for a desalination plant is most often based on land availability near the water demand and on the location of the delivery points of this water to the distribution system. Moreover, potential alternative sites must be selected that meet the following requirements [8]:

- Accessibility from existing main roads, highways, etc.
- Proximity to the points of delivery of the desalinated water to the local distribution system (usually less than 8 km)
- Proximity to power supply for the plant
- Relatively short distance from the source of saline water and the points of concentrate discharge (usually less than 1 km)
- Compatibility with local land planning and zoning requirements
- Location outside of environmentally sensitive areas
- Adequate distance from residential dwellings, hotels, hospitals and other developments whose inhabitants could be sensitive to increased level of noise and traffic during plant construction and operation (at least 30 m)

Based on these requirements, input data into the GIS was collected for the case study (Table 1). Potential locations for SWRO desalination plants were selected in order to meet all of these requirements except local land planning and zoning requirements due to the fact that investigation of land use and possibility of land use change is out of the scope of this study.

2.2.1.2. Water demand. The most common method of allocating baseline water demands is a simple unit loading method [12]. This method involves counting the number of customers that contribute to the demand at a certain point, and then multiplying that number by the unit demand. The boundaries of desalinated water demand are also often influenced by the ability of the alternative water source to supply lower cost water to the same area of demand in order to balance water demand and supply.

In the current study, within the area boundaries water demand is fully supplied by desalinated water.

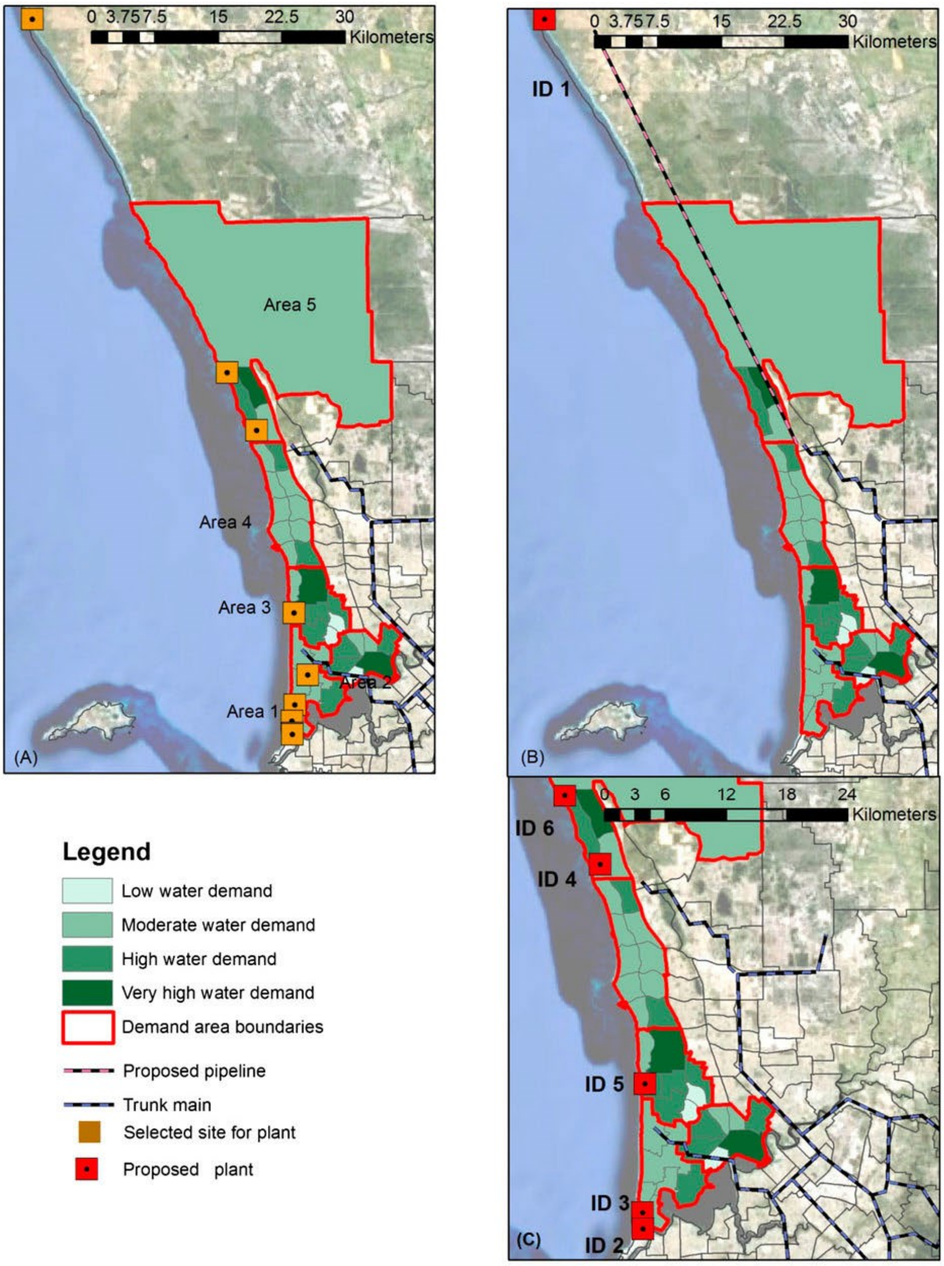

Fig. 1. Geographical illustration for (A) Potential plant sites and demand areas (B) Centralized scenario supply system (C) Distributed scenario supply system.

Table 1
Input data for GIS model

Data group	Individual layers	Source of spatial data (case study)	Notes
Potential site	Water distribution system	[7]	Relevant data were extracted from the original spatial data-sets and modification were made
	Vacant land	[9]	–
	Population	Own data gathering and processing	Spatial data were obtained by combining two sets of data-sets; Population Estimates by Statistical Area Level 2 [10] and Statistical Area Level 2 Digital Boundaries [11]
Water demand	Water demand	Own data gathering and processing	Spatial data were obtained by multiplying spatial population by annual water demand of 145 m^3 [7]
	Current and potential future water sources in the area	[7]	Relevant data were extracted from the original spatial data-sets and modifications were made

The spatial demand of desalinated water was determined by multiplying the number of customers in year 2015 by the annual demand of 145 m^3 [7]. Desalinated water demand was assumed to be constant during the 30-year system lifetime. Input data to the GIS model for building spatial demand of desalinated water is illustrated in Table 1.

2.2.2. Stage 2

The candidate sites and spatial demand of desalinated water identified in Stage 1 served as an input for Stage 2 of the analysis. Water planning scenarios with different size and location for desalination plants are designed in order to satisfy the total desalinated water requirement at the end of the 30-year planning period.

2.3. Stage 3: comparative LCA

The method applied ISO14040 [13], with LCA conducted in four stages: goal and scope, inventory analysis, impact assessment, and interpretation.

2.3.1. Goal and scope

The goal of this LCA is to compare life cycle GHG emissions of the scenarios designed in Stage 2. The functional unit for the study is one cubic meter of water supplied to the demand area in the 30-year lifetime. The scope of this study is primarily cradle to gate. More specifically, each life cycle inventory (LCI) covers the construction phase and the operational phase for SWRO plants, with some coverage of the disposal phase for high impact inputs. The main input flow analyzed were chemical use, materials consumed for membrane replacement, and electricity consumption associated with seawater extraction, water treatment, and the transportation of desalinated water to final users. Disposed waste of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged streams to sewer due to "clean in place" and chemically enhanced backwash, as well as discharged brine to sea were also covered. The decommissioning of the system was not considered. The assumptions for designing the systems are listed in Table 2.

Table 2
System assumptions and description

Assumptions	Description
Water transfer main	
Water transportation head loss	3 meters per kilometer[14]
Motor efficiency	94%
Pump efficiency	82%
SWRO plant	
Treatment process electricity use	Calculated by Rosa software for different sizes[15]
Membrane material	Obtained from [16]
Chemical use, waste disposal, material transportation	Obtained from [4]
Infrastructure capital cost	Calculated by SWRO cost estimator tool[17]

Table 3
Life cycle GHG emissions per functional unit

	Distributed scenario						Centralized scenario					
				GHG emissions (kg CO_2 eq./m^3)						GHG emissions (kg CO_2 eq./m^3)		
Service area	Plant ID	Plant size (m^3/d)	Water transportation distance (km)	Treatment	Water transportation	Total	Plant ID	Plant size (m^3/d)	Water transportation distance (km)	Treatment	Water transportation	Total
Area 1	2	50,000	–	3.29	–	3.29	1	260,000	95	3.16	1.03	4.19
Area 2	3	50,000	–	3.29	–	3.29	1	260,000	95	3.16	1.03	4.19
Area 3	4	60,000	–	3.28	–	3.28	1	260,000	65	3.16	0.81	3.97
Area 4	5	65,000	–	3.28	–	3.28	1	260,000	75	3.16	0.70	3.86
Area 5	6	35,000	–	3.30	–	3.30	1	260,000	55	3.16	0.59	3.75
Total	–	–	–	–	–	3.28	1	260,000	95	–	–	4.00

2.3.2. LCI analysis method

A LCI is the phase of LCA aimed at compiling all output emissions and wastes and also input resources as environmental flows[18]. In this study, LCI for construction phase was defined by economic input–output based (IO-based) LCI method. For operational phase, LCI was obtained by process based LCI method. Using economic input–output for construction phase was due to the process data limitation. The foreground data for the construction phase and operational phase are in monetary and physical units, respectively. Operational phase background data was mostly selected from an Australian database [19] and the grid electricity and transportation were selected for WA. For material and processes, which were not available in the Australian database, Ecoinvent library was used as a supplement database[20]. Construction phase background data are selected from GHG Input–Output LCI for Australia [21].

2.3.3. Life cycle impact assessment (LCIA) method

LCIA is the final phase of LCA in which inventory data are converted into impact results through the use of appropriate algorithms or indicators, to simplify understanding and assessing the environmental impact of a product system [18]. GHG emissions in kg CO_2 equivalent was calculated based on the Intergovernmental Panel on Climate Change 2007 method for the timeframe of 100 years with Simapro software [22].

3. Results and discussion

By implementing the GIS modeling as outlined in Section 2, desalinated water demand and most suitable locations for medium-scale desalination plants were identified in the case study area as illustrated in Fig. 1(A). In Stage 1, 8 suitable locations were identified for medium and small-sized SWRO desalination plants. In Stage 2, based on spatial desalinated water demand and potential sites, two water planning scenarios (centralized scenario and distributed scenario) were designed to supply the demand as illustrated in Fig. 1(B) and (C). In the centralized scenario, desalinated water was supplied to the demand area through a large centralized plant located nearly 95 km from demand area. In the distributed scenario, desalinated water was supplied locally by five decentralized plants located in the demand areas.

Table 3 presents the life cycle GHG emissions of two scenarios. The life cycle GHG emissions have been validated through comparison with other studies [4,5]. Results indicate that the distributed scenario has 20% lower life cycle emissions than the centralized scenario. Reducing the water transportation pumping in the distributed system plays a positive role in reducing GHG emissions in distributed water planning. In the distributed scenario, the highest GHG emissions per functional unit belong to Area 5. This is due to the fact that desalinated water is supplied to this area through an onsite desalination plant with a capacity of 35,000 m^3/d. The treatment process electricity use is slightly higher in the smaller plants due to the lower efficiency in centrifuge pumps in lower flow rates and consequently higher GHG emissions. Moreover, higher GHG emissions arise from construction of the water treatment plant buildings due to the diseconomy of scale for construction phase in small plants. In contrast, lowest GHG emissions per functional unit belong to Area 5 in centralized planning. This is due to the low water transportation distance between large SWRO plant and this demand area.

Generally, the results show that site-specific parameters of plant location and size could significantly affect the environmental impact of SWRO desalination plants. For this case study of the Perth northern metropolitan area, distributed water planning has lower GHG emissions than centralized water planning.

4. Conclusion

In this study a three-stage methodology was developed to assist in SWRO desalination plant location and size decision-making considering the environmental performance of the systems. Stage 1 used a GIS-based approach to identify potential sites and spatial desalinated water demand in the area under study. Stage 2 used input data from Stage 1 to develop water supply scenarios. Stage 3 compares the scenarios to obtain the optimum water supply scenario considering environmental impact of the system. To illustrate the model, a case study was applied. Two common scenarios of centralized and distributed water planning were compared in Perth, WA. Generally, results showed that site-specific parameters of plant location and size could significantly affect the environmental impact of SWRO desalination plants. For the case study of Perth northern metropolitan area, distributed water planning has better environmental performance than centralized water planning.

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4.3. Chapter summary and link to the next chapter

This chapter addresses the third research question, namely, **do SWRO desalination plants size and location affect the life cycle environmental performances of their supply chain.** In this chapter a Geographical Information System (GIS) based method is introduced to assist in desalination planning. The method's applicability was tested using data for the northern corridor of Perth, Western Australia (WA). Two scenarios of centralised and decentralised seawater desalination options were compared based on their life cycle GHG emissions. The results show that desalination plants site specific decisions such as location and size has influence on the supply chain GHG emissions. The method developed in this chapter progressed (Chapter 5) to include other environmental impacts and cost in the analysis.

CHAPTER 5. QUANTIFY AND COMPARE THE LIFE CYCLE ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF CENTRALISED AND DECENTRALISED SWRO DESALINATION OPTIONS

5.1. Attribution

Maedeh P. Shahabi wrote all sections of this paper, carried out all LCA and LC modellings, designing conceptual scenarios and conducted all data analysis. Adam McHugh acted as co-supervisor critically read various draft of paper and provided advice in cost estimation. Goen Ho acted as co-supervisor and read various drafts of papers and provided feedback regarding the scope of the study, scenario development and sensitivity analysis. Martin Anda acted as principal supervisor and revised several drafts of the paper and gave feedback on the case study data and supply system design.

Maedeh P. Shahabi: +80%

5.2. Paper 4: Shahabi, M. P., McHugh, A., & Ho, G. (2015). Comparative economic and environmental assessments of centralised and decentralised seawater desalination options Desalination, 376, 25-34.

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Comparative economic and environmental assessments of centralised and decentralised seawater desalination options

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HIGHLIGHTS

• Comparative life cycle assessment of decentralised and centralised desalinated water supply
• Integration of spatial case study scenarios with LCA and levelised cost analyses
• Using the case of Perth, Australia, future planning of desalination was evaluated.
• Decentralisation is a potential strategy to reduce environmental impacts of desalination.

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ABSTRACT

This study presents comparative life cycle assessments (LCAs) and levelised cost (LC) analyses of desalination supply systems, integrated with a spatial–temporal model at three geographical scales: a *centralised scenario* and two alternative *decentralised scenarios*. For the *centralised scenario* we focused on a proposed 320,000 m^3/day SWRO desalination plant to support future urban expansion in the northern corridor of Perth, Western Australia. The alternative, *decentralised scenarios* each integrate several medium sized plants into the same geographical water demand area as the *centralised scenario* and also produce 320,000 m^3/day in total. Results indicate that environmental impacts would be ~20% lower and LC 7% to 18% lower for the *decentralised scenarios* than for the *centralised scenario*. Contribution analysis revealed that, for the *centralised scenario*, although economies of scale resulted in lower environmental impacts from the desalination plant construction and operation phases, these savings were outweighed by the environmental impacts associated with the construction and operation of the water transfer mains required to connect the large plant to the network. Perth water stakeholders and policy makers can use our results to inform development decisions, and the proposed LCA method can be implemented in other metropolitan areas for desalination planning.

1. Introduction

1.1. Background

Desalination has a long history of supplying clean water in arid environments such as the Middle East, the Caribbean and the Mediterranean. However, recent climate change, combined with population growth and limited availability of terrestrial water sources, has hastened the widespread expansion of the technology. Freshwater resources are scarce, whereas desalinated seawater is climate independent and only limited by the capital and energy required to produce it. Moreover, approximately three billion people — about half of the world's population — live within 200 km of a coastline [1], so seawater is an accessible resource. A recent trend in seawater desalination is the construction of large capacity plants, and this has significantly contributed to freshwater supply for coastal cities around the globe. Large desalination plants built between 2000 and 2005 were typically designed to supply 5 to 10% of the drinking water of coastal cities. More recently, regional or national seawater desalination projects in countries such as Spain, Australia, Israel, Algeria and Singapore have been planned to fulfil 20 to 50% of a city's long term drinking water needs [2]. Desalination plants enjoy economies of scale in treatment facility construction. However, potential sites for large plants need to meet specified criteria such as proximity to the ocean, access to a power source and minimal impact on environmentally sensitive areas [2]. Obtaining land planning and environmental regulatory approvals for large plants and maintaining ongoing compliance can be challenging in developed countries with effective environmental legislation and governance. Identifying sites that meet all of these criteria — while having enough acreage to accommodate a large-scale plant, its various components and the necessary buffers — is generally not possible in established

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urban areas. These regulatory barriers result in large desalination plants being constructed far from the location of water demand and consequently long water transportation distances, compared to those that would apply if plants were instead located within the distribution network. Long distance water transportation has environmental and economic burdens that should be considered in the planning stage.

Currently, reverse osmosis (RO) is the leading technology for seawater desalination [3]. When compared with conventional sources such as dams, seawater reverse osmosis (SWRO) plants are a more desirable option for decentralisation because SWRO has a scalable, modular design whereas conventional water sources such as dams lack design and scale flexibility. Dam sites are also highly restricted by natural factors such as site topography, catchment conditions, salt levels and soil materials while the only naturally restricting factor for desalination plants is proximity to treatable water.

This paper argues for the need to identify the optimum geographical scale of a desalination system and thus resist the default mindset of "big is better" [4] in the water sector. A framework for investigating the optimum geographical scale for water planning using spatial and temporal case study data (e.g. land availability, water demand, and existing pipeline network) coupled with hybrid life cycle assessment (LCA) and levelised cost (LC) analyses is proposed. Comparative LCA and LC are demonstrated for three geographical scale desalination supply systems, these being one centralised scenario and two decentralised scenarios. For the centralised scenario we focus on a new 320,000 m^3/day SWRO desalination plant. The decentralised scenarios — where several smaller plants also produce, 320,000 m^3/day in total — are proposed as alternative water supply options for the same area of demand. Centralised planning of desalination supply system often leads to economies of scale in the construction phase. However, engineers and decision makers need to make sure that centralisation generates overall system benefits rather than only shifting environmental and economic burdens from the treatment facility's construction to other sub-systems such as distribution network construction and/or the operational phase. Understanding which planning strategies may be most beneficial in the long run requires a system approach that not only covers all life cycle stages of the supply system at a high level of detail, but also considers a range of environmental impacts to avoid burden shifting between different environmental impact categories.

1.2. Perth case study

Perth, Western Australia (WA) has been chosen as a case study due to the availability of comprehensive site-specific data and the appropriateness of its geography, geology, climate and urban form to the employment of the desalination technologies under examination. The metropolitan area of Perth has a low-density urban form spread along the coast of the south west of Western Australia and is built predominantly upon ancient sand dunes. Since about 1975, south west Australia has experienced a significant reduction in rainfall which, combined with population growth, has led to an increased dependence upon desalination to secure its water supply [5]. Perth is currently the largest user of seawater desalination among Australian cities [6]. Half of the water supply for Perth and surrounding areas is sourced from two large seawater reverse osmosis (SWRO) plants; the Southern Seawater Desalination Plant (SSDP) and the Perth Seawater Desalination Plant (PSDP) contribute 320,000 m^3/day and 145,000 m^3/day respectively. A new 320,000 m^3/day SWRO desalination plant, the Northern Seawater Desalination Plant (NSDP), was proposed to support future urban expansion in the northern corridor of Perth and to replace a loss of capacity in the groundwater water supply system resulting from a persistent trend in reduced rainfall in its catchment area [7]. The SSDP and PSDP are located 130 and 30 km south from Perth city centre, respectively. The NSDP would be located 90 km north of Perth's city centre.

The water supply infrastructure in Perth is operated by the government-owned enterprise, Water Corporation. Water Corporation purchases electricity for its two large desalination plants (total design capacity of 465,000 m^3/day desalinated water) from three wind and solar farms annually and consumes the equal amount of electricity from WA's electricity grid [8]. The pairing of desalination plant with wind and solar farms can reduce supply chain GHG emissions by 90% per unit of water [9] provided the pairing results in renewable energy production that is additional to any mandated portfolio standard. However, the purchase of renewable energy may come at a price premium and is susceptible to changes in government policy. The current study evaluates the decentralisation of SWRO desalination plants as a possible strategy to reduce the life cycle impacts of desalinated supply systems, independently of the energy supply choice.

1.3. Literature review

Geographical scale assessment of water supply can be tracked back to the cost modelling of water supply systems by Clark and Stevie in 1981 [10]. Technical, economic, environmental and social performance of different scales of water and sanitation supply options such as stormwater recycling, grey water recycling, truck distribution [11], wastewater treatment [11–14], desalination [11,15–18] and rainwater tank [19] were investigated in the literature employing a range of different quantitative and qualitative methods. Methods included mathematical optimisation [15–17], multi-criteria decision analysis [11,13], sustainability analysis [12], specific net present value [14], and statistical analysis [19]. These quantitative and qualitative methods were applied to different case studies in developing and developed countries. While these studies have acknowledged the significance of decentralisation as a planning strategy for improving water supply economic and environmental performance, there is a lack of application of full LCA perspective in the assessments. A few studies have considered the carbon footprint of a supply option's operational phase in their geographical scale assessment rather than a holistic environmental appraisal [16–18]. Moreover in these works, there is a lack of detailed environmental impact data for various sizes of treatment plant and pipeline infrastructure. Life cycle assessment, standardised by the International Organisation for Standardisation (ISO) [20] is a powerful tool for environmental impact assessment of the systems that produce goods or services. Full LCA can be used to identify cases of burden shifting, i.e. between different environmental impact categories (e.g. climate change versus ozone layer depletion) or between supply system life cycle stages (e.g. construction phase versus operational phase). Developing desalination planning strategies for metropolitan areas requires a system approach that covers the environmental and economic life cycles at a high level of detail. To the best of our knowledge, previous studies have not considered the geographical scale of a supply system when evaluating the supply chain contributions to the life cycle environmental impacts and economic costs of desalination. The objective of this study is to conduct the full LCA of the proposed NSDP using a hybrid Economic Input–Output (EIO) environmental LCA approach coupled with temporal and spatial modelling of the case study scenarios, and then to use these estimates to complete a comparative LCA and LC of the centralised and decentralised desalination systems modelled. The method has the potential to be used in geographical scale assessments of proposed water supply systems more generally.

2. Methodology

2.1. Overview

We created a spatial–temporal database of forecast desalinated water demand from 2015 to 2035, vacant land for accommodating plants and water storage facilities, and existing pipeline infrastructure, in order to design scenarios at different geographical scales. Scenarios were compared with each other using hybrid Economic Input–Output (EIO)–LCA and LC. All spatial related tasks were performed using ArcGIS version 10. LCA analyses were conducted with Simapro 7. Decision graphs were produced for comparing the environmental and economic performances of scenarios quantitatively. The system definition and its characteristics are presented in Fig. 1. The EIO–LCA was selected in order to capture system performance associated with economies of scale in the construction phase.

2.2. Geographical scale selection and spatial–temporal model of case study system scenarios

For the case study, desalinated water demand was assumed to emanate from 28 suburbs in the Perth northern metropolitan area. Existing local government boundaries were used for defining the geographical scale in the modelled scenarios. Desalinated water demand maps (Fig. 2a) were generated for the case study for 20 years (2015–2035) based on the suburbs' current population [21,22] and projected population growth of 4.5% per annum [23]. Perth's annual water use per capita was assumed to be 135 m^3 in year 2015 and to achieve 15% saving by 2035 [7]. In the *centralised scenario*, a large plant was located at the proposed NSDP site obtained from a published report on water planning for Perth by 2060 [7]. Four sites were chosen to accommodate the proposed plants in the *decentralised scenario, cluster scale 1*, and eleven sites were chosen for the *decentralised scenario, cluster scale 2*. Land area required to accommodate each plant size was obtained from the literature [24]. Perth land use maps [25], site observation and engineering judgement were employed for selecting plants sites. The three scenarios were defined, designed and compared for their life cycle environmental and economic performances. These were:

- *Centralised scenario. Base Case* — a single SWRO desalination plant with a capacity of 320,000 m^3/day. Construction of 75 km of trunk main to connect the plant to the existing supply system was accounted for in this scenario. The water demand area for the plant was comprised of 28 suburbs (Fig. 2c).
- *Decentralised scenario, cluster scale 1* — four SWRO desalination plants with sizes ranging between 65,000–100,000 m^3/day with a cumulative design capacity of 320,000 m^3/day. The service zone of each plant consisted of four to ten suburbs (Fig. 2d).
- *Decentralised scenario, cluster scale 2* — eleven SWRO desalination plants with sizes ranging between 15,000–50,000 m^3/day with total design capacity of 320,000 m^3/day. The service zone of each plant consisted of one to four suburbs (Fig. 2e).

Detailed information on plant design capacity, location, service area and pipeline distance for each plant scenario is presented in Table S1–S3 of the supplementary documents. All scenarios are technologically and geographically feasible according to our best of knowledge, but we do not make any claim regarding the likelihood of their implementation.

2.3. Hybrid input–output environmental life cycle assessment

To quantify environmental performance of the scenarios, the study employed a hybrid-LCA approach which combines process–LCA and EIO–LCA models [26]. An EIO–LCA model augments national or regional Economic Input–Output data with a pollution inventory for each industry sector to obtain the supply chain environmental flows associated with a product. EIO–LCA was used to obtain life cycle environmental impacts associated with SWRO plant process facilities, buildings and their connected trunk mains through the construction phase, as described in Section 2.3.2. The process–LCA was used for modelling

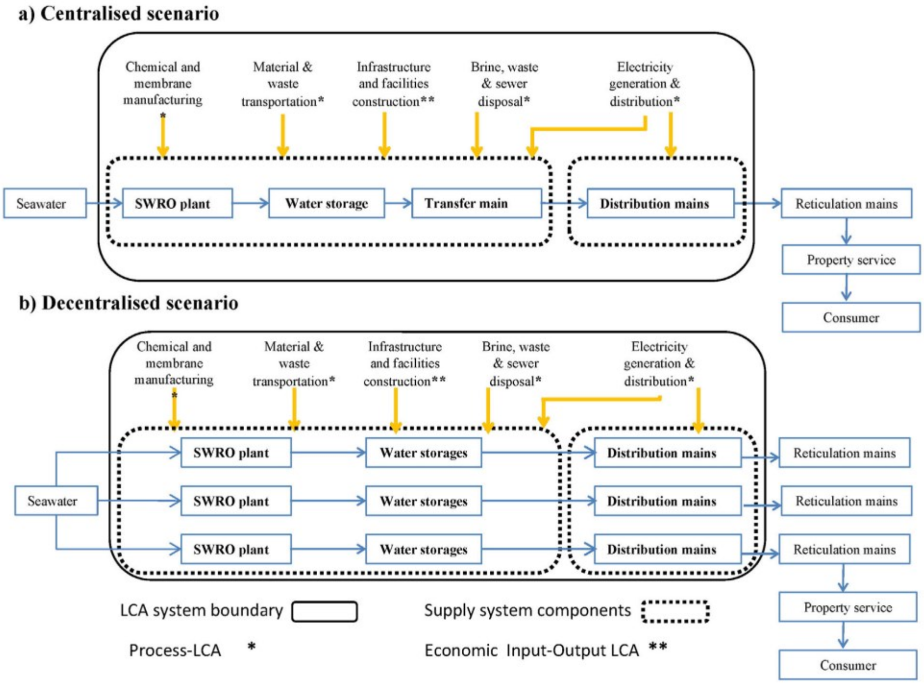

Fig. 1. System definition — the supply system design was based on spatial–temporal scenario data for the case study and selected geographical scale. Upstream input flows were modelled by process–LCI or EIO–LCI as illustrated. The number of distributed facilities in the decentralised scenario diagram is for illustrative purposes.

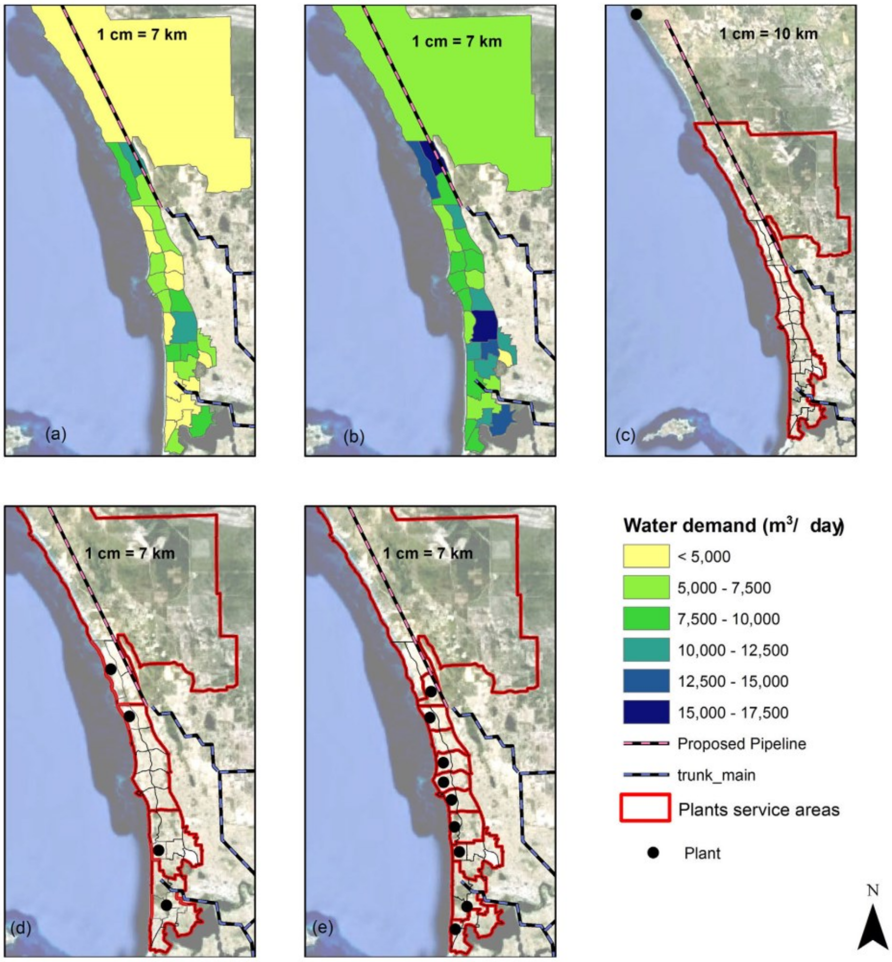

Fig. 2. a) Spatial water demand map in year 2015. b) Spatial water demand map in 2034. c) Centralised scenario plant location and its supply zone. d) Cluster scale 1, plant locations and their supply zones. e) Cluster scale 2, plant locations and their supply zones.

environmental performances associated with the system's operational phase as described in Section 2.3.3. The results of both models were combined to obtain the overall life cycle emissions associated with each SWRO scenario.

2.3.1. Functional unit and system boundaries

The same functional unit was chosen for each scenario to make them comparable, this being supplying 1 m^3 of desalinated water to the defined demand area in Perth, WA. A time boundary of 20 years was selected for each scenario. The scope of this study was cradle to gate. Each LCA covered the construction and operational phase of the SWRO plants and the water transportation system, with some coverage of the disposal phase. The main flows in the operational phase were chemical use, materials consumed for membrane replacement, electricity consumption associated with seawater extraction, water treatment, and water delivery pumping. Disposal of membranes and sludge to landfill at the end of their assumed service life was also included in each LCA. Discharged streams to sewer due to 'clean in place' and chemically enhanced backwash and discharged brine to sea were also covered. The scenarios' common system boundary is illustrated in Fig. 1.

2.3.2. Emissions from operational phase

Process specific parameters for the conceptual RO process designs were chosen from the literature. All scenarios were considered to have a single pass RO system with a 50% recovery ratio design as the core treatment technology. Two software tools were used to design the RO process at different plant sizes. These were the ROSA system design software [27], and the Microsoft Excel based program, ERI [28]. Each pressure vessel in the RO system was assumed to contain eight membrane elements connected in series. Feed water quality for designing RO trains was based on Indian ocean seawater quality [29]. The design parameters and assumptions for different plant sizes are summarised in supplementary document, Table S4.

Assumptions associated with site-specific parameters were chosen to reflect the features of the Perth metropolitan area. In all scenarios, transportation distances for chemicals, membrane materials and

Table 1
Operational phase life cycle inventory for each scenario's per m^3 water supplied.

Subsystems	Unit	Input and output flows				
		Base case	Cluster scale 1	Cluster scale 2	Description	Supplementary databases for LCI
Seawater extracted	m^3	2.20	Same as base case scenario	Same as base case scenario	In all plant sizes, the recovery ratios were assumed to be 90% for pre-treatment. The RO recovery ratio was assumed to be 50%.	Resources extracted from ocean
Average electricity use in seawater extraction	kWh	0.05	Same as base case scenario	Same as base case scenario	The assumed energy requirement for transferring seawater to the treatment plant was based upon a seawater density of 1024 kg/m^3, pump efficiency of 94% and electric motor efficiency of 82%. For all scenarios, the seawater transfer distance was assumed to be 500 m with a pumping elevation of 15 m. Head loss due to friction was assumed to be 3 m per kilometre [31].	Australian high voltage electricity data [32]
Average electricity use in disk filter, ultra filtration and cartridge filter facilities	kWh	0.3	Same as base case scenario	Same as base case scenario	The average electricity use in pre-treatment is same in all scenarios and adopted from literature [33].	Australian high voltage electricity data [32]
Average electricity use in RO plants	kWh	2.65	2.70	2.80	Refer to supplementary document, Table S4 for design assumptions and electricity breakdown for each desalination plant size.	Australian high voltage electricity data [32]
Average electricity use in distribution network	kWh	0.140	0.006	0.005	The amount of electricity used in potable water transportation was calculated assuming a water density of 1000 kg/m^3, pump efficiency of 94% and electric motor efficiency of 82%. The water distribution distances in each scenario for each suburb are presented in supplementary document, Table S1–S3. Head loss due to friction in water transportation pipelines was assumed to be 3 m per kilometre [31]. Refer to supplementary document, Table S1–S3 for distribution electricity use breakdown for each desalination plant size.	Australian high voltage electricity data [32]
Chemical	g	Sodium hypochlorite; 1.94, sulphuric acid; 0.69, sodium metabisulphite; 0. 07, citric acid; 0.28, Sodium hypochlorite; 1.63, citric acid; 0.65, detergent; 2.72, caustic soda; 0.4, biocide; 9.86	Same as base case scenario	Same as base case scenario	The amount of chemical use in extraction and pre-treatment is same in all scenarios and adopted from literature [33].	Chemical manufacturing were selected from the Ecoinvent [34] or Australasian database [32].
Membrane	g	Polypropylene; 0.05, polyethylene; 0.50, polyurethane; 0.14, acrylonitrile-butadiene-styrene; 1.27, polyamide; 0.14	Same as base case scenario	Same as base case scenario	The amount of membrane use in pre-treatment and RO is same in all scenarios and adopted from literature [33].	Membrane material production plus extrusion and injection moulding were obtained from Ecoinvent [34] or Australasian database [32].
Brine	m^3	1.20	Same as base case scenario	Same as base case scenario	In both scenarios brine has TDS of 80,000 mg/L.	Discharge to ocean for brine.
Landfill	g	2.11	Same as base case scenario	Same as base case scenario	–	Plastic landfill was selected for membrane disposal from Australasian database [32].

waste were assumed to be the same as those required for the SSDP and were obtained from the literature [30]. The life cycle inventories for each scenario's operational phases are provided in Table 1.

2.3.3. Emissions from construction phase

The EIO–LCA method was used to quantify sector-specific life cycle environmental impacts from the construction of plant process facilities, seawater extraction equipment, buildings and storage tanks. In both scenarios, construction of plants process facilities, seawater extraction equipment, buildings and storage tanks were included. For the centralised scenario, construction of 75 km of trunk main to connect the desalination plant to the existing Perth water supply system was also included in LCA analysis.

An EIO–LCA method augments national or regional Economic Input–Output data with a pollution inventory for each industry sector to obtain the supply chain environmental flows associated with a product. A number of previous studies [35–37] used this method for estimating the environmental impacts associated with the construction phase of desalination plants. In this study, the treatment plants, storage tanks and pipeline construction costs were used to estimate impacts from the construction phase and related upstream activities. The 'other non-residential structures' industry sector was used for the accounting of construction phase emissions. All monetary values were normalised to 2002 US$ in order to match the data for the USA Input–Output 2002 database in Simapro LCA software. This is the most recent update to this database that relates financial flows to environmental impacts. Capital expenditure values were obtained from the literature [24] for each facility, converted to 2002 US$ producer prices, summed, divided by the water expected to be supplied over a 20 year lifetime in m^3, and entered into the final demand vector of the EIO–LCA model [38] to estimate emissions. These capital expenditure values are listed in Table S5, supplementary document.

2.3.4. Life cycle environmental indicators

Ten CML 2001 [39] obligatory impact indicators at a mid-point level were chosen as life cycle environmental indicators in this study. These impact indicators include: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Layer Depletion (ODP), Human Toxicity Potential (HTP), Fresh Water Aquatic Eco-toxicity (FAETP), Marine Aquatic Eco-Toxicity Potential (MAETP), Terrestrial Eco-toxicity Potential (TETP) and Photochemical Oxidation Potential (POCP).

Monte Carlo simulation was used for uncertainty analysis facilitated by an algorithm in the Simapro software [38]. The material, energy and monetary flows probability distributions were estimated by employing a qualitative assessment method which is documented comprehensively in the literature [40]. In this method uncertainty factors (expressed as a contribution to the square of the geometric standard deviation) are estimated for each inventory flows based on a semi-quantitative approach including expert judgement and assessment of data quality. The assigned uncertainty factors, the estimated square of the geometric standard deviation for inventory flows and their probability distributions are listed in supplementary document Table S6.

2.4. Levelised cost

This study employed a LC analysis to compare the economic performance of each scenario. LC is the real price at which a long term contract would need to be negotiated in order for a project to breakeven in net present value (NPV) terms. We partitioned the LC metric into levelised capital cost (LCC) and levelised operational cost (LOC) components as follows:

$$\mathrm{LC} = \mathrm{LCC} + \mathrm{LOC}. \tag{1}$$

LCC is given by

$$\mathrm{LCC} = \frac{\sum_{t=0}^{n} \frac{K_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}}, \tag{2}$$

where K_t denotes the capital cost (capex) accruing in year t ($), Q_t water production in year t (m^3), r the weighted average cost of capital (WACC) — i.e. the rate of return required to service the combined costs of equity and debt — and n the amortisation period.

LOC is given by

$$\mathrm{LOC} = \frac{\sum_{t=0}^{n} \frac{V_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}}, \tag{3}$$

where V_t denotes the operational cost (opex) accruing in year t ($). All capital and O&M costs except electricity, land and labour for both scenarios were adopted from the literature [24] and were adjusted to 2013 Australian dollars (AU$) using exchange rates obtained from Reserve Bank of Australia database [41] and producer price indices

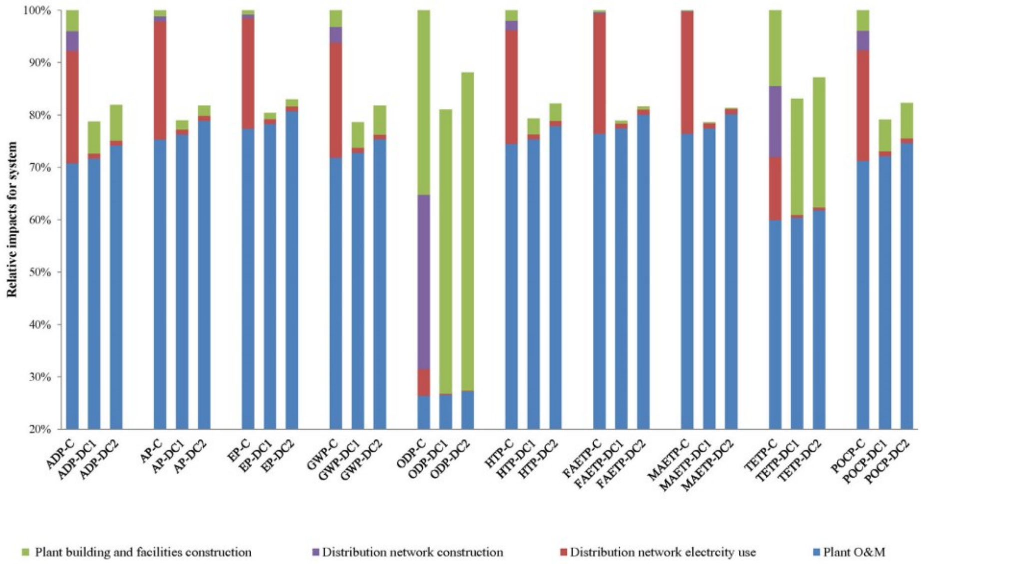

Fig. 3. Relative cumulative environmental impacts and contribution analyses of the scenarios, C: centralised scenario, DC1: decentralised scenario, cluster scale 1, DC2: decentralised scenario, cluster scale 2. The maximum values per functional unit obtained for each impact category are: ADP: 2.94E−02 kg Sb, AP: 2.45E−02 kg SO_2, EP: 1.58E−03 kg PO_4, GWP: 4.15E+00 kg CO_2, ODP: 2.20E−07 kg CFC-11, HTP: 1.13E−01 kg 1,4-DB, FAETP: 9.15E−01 kg 1,4-DB, MAETP: 2.91E+03 kg 1,4-DB, TETP: 2.17E−03 kg 1,4-DB, POCP: 9.72E−04 kg C_2H_4.

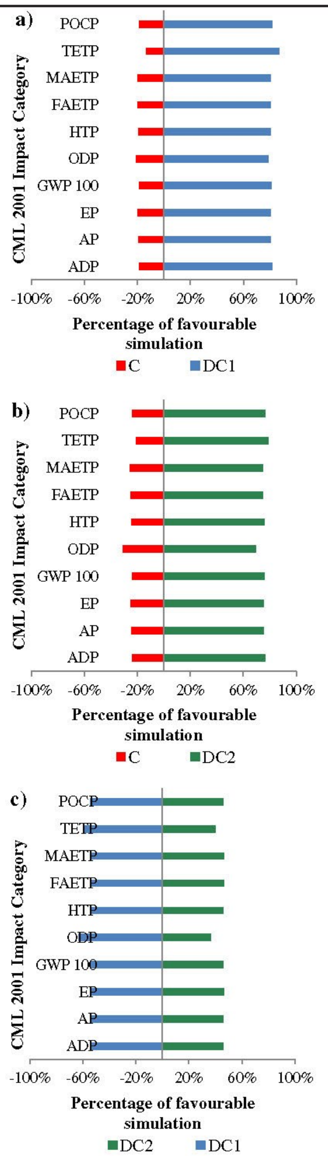

Fig. 4. Uncertainty analysis results (Monte Carlo simulation with a 95% confidence interval, run 1000 times), C: centralised scenario DC1: decentralised scenario, cluster scale 1, DC2: decentralised scenario, cluster scale 2.

obtained from Australian Bureau of Statistics database [42]. Land requirements in hectares were obtained from [24] and unit cost of land was assumed to be 300AU$/$m^2$. The amount of electricity use was based on conceptual design (Section 2.3.3) and the wholesale electricity price of 143AU$ per MWh was obtained from the literature [43]. The number of full time staff required for routine maintenance and operation were adopted from [24]. Labour cost was calculated based on a 2013 wage of 68,203AU$ per year. The real WACC of 6.62% proposed by the Western Australian Water Corporation was selected for the LC analysis [44]. All plants, their connected storage tanks and trunk mains were assumed to be constructed during the 2014 financial year, with production commencing the following year. Plant capacity factors were assumed to increase from 50% in financial year 2015 to 85% in financial year 2034.

3. Results and discussion

3.1. LCA

Fig. 3 shows the relative impacts of the scenarios and contribution of each subsystem to total impacts across the ten environmental indicator categories. The scenario with the greatest environmental impact in each category was normalised to 100%. Across all impact categories, the centralised scenario had ~20% greater environmental impacts than the decentralised scenarios. This was due to the environmental impacts associated with electricity use for long distance water pumping and, to a lesser extent, the construction of the long distance transfer main. The small and medium sized plants in the decentralised scenarios do not achieve the economies of scale enjoyed by the large plant in the centralised scenario during construction. However, the small and medium sized plants are located close to the point of demand and so benefit from lower environmental impacts associated with electricity input requirements for water delivery.

Contribution analysis revealed that, in all scenarios, plant O&M in the treatment process was the dominant source of environmental impact over the life cycle (~60 to ~81%) with the exception of ODP (~27%) where the plant building & facility construction phase was the dominant impact contributor (61% for the *decentralised cluster scale 2*, 54% for the *decentralised cluster scale 1* and 35% for the *centralised scenario*). Otherwise, the contribution of plant construction to total environmental impact was relatively small (less than 7% of the total impact), with the exception of the TETP indicator (25% for the *decentralised cluster scale 2*, 22% for the *decentralised cluster scale 1* and 14% for the *centralised scenario*). Moreover, decentralised cluster scale-2 scenario had the greatest O&M environmental impacts for all indicators. This was due to lower pump efficiencies at lower flow rates in the RO process of the small plants employed in the decentralised cluster scale-2 scenario, and therefore higher environmental impacts associated with electricity use per m^3.

Uncertainty analysis was conducted to assess the influence of variations in process data and assumptions on the LCA results for paired scenarios. Monte-Carlo simulation was used to generate samples from lognormal distributions with scale parameters based on the data input uncertainty factors outlined in Table S6 of the supplementary document. Fig. 4 shows the comparative Monte-Carlo simulation results of 1000 runs conducted for each scenario pair: centralised vs cluster scale 1; centralised vs cluster scale 2; and cluster scale 1 vs cluster scale 2. The diagrams report the percentage of runs for which one scenario achieved a lower impact than its pair over the range of impact categories. The simulation resulted in the decentralised scenario, cluster scale 1 achieving lower environmental burdens than the centralised scenario for 79%–87% of the runs across the impact category (Fig. 4a). Results in Fig. 4b show that the decentralised scenario, cluster scale 2 achieved lower environmental impacts than the centralised scenario for 69%–79% of the runs across the impact categories. The decentralised scenario, cluster scale 1 had lower environmental impacts than the decentralised scenario, cluster scale 2 for 54%–64% of the runs.

3.2. Economic assessment

Table 2 reveals that the LC across the scenarios lies between 3.49AU$/$m^3$ and 4.25AU$/$m^3$ of desalinated potable water supplied to final demand. The *cluster scale 1 scenario* has the lowest LC, and the *centralised scenario* the highest. For all three scenarios, the LCC (plant and pipeline) component is much greater than the LOC (all operational inputs) component. 'Variable O&M' costs (membrane, chemical,

Table 2
Levelised cost breakdown of each scenario for functional unit of 1 m^3 water of desalinated water.

Activities	Centralised scenario (base case)	Decentralised scenario, cluster scale 1		Decentralised scenario, cluster scale 2	
	LC component (AU$/$m^3$)	LC component (AU$/$m^3$)	Δ from base case (AU$/$m^3$)	LC component (AU$/$m^3$)	Δ from base case (AU$/$m^3$)
Building and facilities construction (capex)	1.547	2.374	0.827	2.698	1.151
Overhead cost (capex)	0.030	0.029	−0.001	0.045	0.015
Land cost (capex)	0.175	0.272	0.097	0.312	0.137
Transfer main pipeline construction (capex)	1.628	0.000	−1.628	0.000	−1.628
Variable O&M (opex)	0.674	0.680	0.006	0.696	0.022
Fixed O&M (opex)	0.058	0.129	0.071	0.214	0.156
Distribution network electricity use (opex)	0.140	0.006	−0.134	0.006	−0.134
LCC (total capex)	3.380	2.675	−0.705	3.056	−0.324
LOC (total opex)	0.872	0.815	−0.056	0.916	0.044
LC (total)	4.252	3.490	−0.761	3.971	−0.280

electricity, and replacement parts) contribute in the rage of 16% to 19% to LC, while 'fixed O&M' (labour and insurance) costs are relatively small contributors to LC (1% to 5%). The LC contribution of 'distribution network electricity use' — mainly water delivery pumping costs — are more than 22 times greater for the *centralised scenario* than for the *decentralised scenarios* due to the distance of the centralised plant from consumers.

Entries in the columns of Table 2 titled 'Δ from *Base Case*' give the difference in each LC component between the *centralised scenario* (the base case) and the relevant *decentralised scenario*, with a positive number indicating a move away from the base case to a decentralised scenario would increase the LC component, and vice versa. The analysis reveals that the *cluster scale 2 scenario*, which employs the smallest sized plants of the three scenarios, has a 'building and facility construction' LC component that is 1.15AU$/$m^3$ higher than for the *centralised scenario*, whereas for the *cluster scale 1 scenario*, which employs the medium sized plants, that same component is 0.83AU$/$m^3$ higher. Moreover, the 'fixed O&M' LC component for the *cluster scale 2 scenario* is 0.16AU$/$m^3$ higher, and for the *cluster scale 1 scenario* is 0.07AU$/$m^3$ higher than for the *centralised scenario*, mainly due to the additional labour costs required to maintain and operate the smaller distributed plants. These results reflect economies of scale. However, the economies of scale enjoyed by the centralised plant are in this case outweighed by the costs of integrating it into the water supply network — i.e. the construction of a 75 km, high capacity water trunk main — contributing 1.63AU$/$m^3$ to LC. Moreover, the cost of operating that pipeline adds another 0.13AU$/$m^3$ to the *centralised scenario's* LC, this being mainly electricity expenditure for pumping.

3.3. Influence of system boundary on LC and LCA results

Fig. 5 shows the influence of selecting a system boundary that excludes the water transport and distribution network infrastructure from analysis. It reveals that this would result in underestimation of LC by 1.77AU$/$m^3$ and GWP by 1.00 kg CO_2 e/m^3 for the *centralised scenario*. For the *decentralised scenarios*, it would result in underestimation of GWP by 0.04 kg CO_2 e/m^3. When the complete supply chain is considered in the LC analysis, the lower construction costs associated with the decentralised plant's economies of scale are outweighed by pipeline construction and operational costs. Similarly, the lower per unit life cycle greenhouse gas emissions due to electricity input economies of scale in the plant are outweighed by emissions due to the increased electricity input requirements for pumping water through the pipeline. Ignoring the water pipeline from analysis would erroneously suggest that the centralised planning solution is Pareto optimal, whereas decentralised planning is actually more efficient in this case.

By solving numerically for the trunk main length while holding other parameter values constant, we found that the *centralised scenario*'s LC would fall below that of the decentralised *cluster scale 1* scenario if the required pipeline length was reduced to less than 35 km. Using the same approach for greenhouse gas emissions we found that the trunk main length would need to be less than 4 km in length before the *centralised scenario* would outperform the *cluster scale 1 scenario* on that basis. This observation is consistent with the observation in Section 3.1 above that pipeline operation is a substantial contributor to environmental impacts. This implies that the relative economic performance of centralised versus decentralised desalination systems is highly sensitive to pumping distance, whereas the relative greenhouse gas performance is not.

3.4. Regulatory challenges of decentralised desalination planning

In desalination supply, regulatory challenges and public support are identified as two critical factors to the initiation and success of projects [45]. Generally new approaches to urban water supply such as the decentralisation approach proposed in this study have often been controversial and their successes is dependent upon creation of an enabling environment [46] that incorporates factors including government

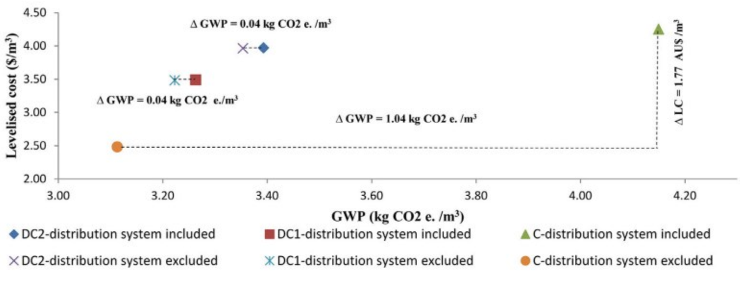

Fig. 5. Relation between GWP and LC of the three different systems with exclusion and inclusion of distribution network from the system boundaries. Δ LC: changes between centralised scenarios LC due to exclusion of pipeline in system boundary, Δ GWP: changes between centralised scenarios GWP due to exclusion of pipeline in system boundary.

support, financing opportunities and socio-cultural acceptance [47]. Compared to centralised planning, decentralised planning of desalination may raise further regulatory challenges associated with land use change and zoning in developed metropolitan areas. For example, obtaining planning and environmental regulatory approvals for land and maintaining ongoing compliance can take longer than expected in developed metropolitan areas with effective environmental legislation and governance, impacting project timing and budget. While this study proposed a quantitative life cycle framework for the assessment of decentralisation, other significant factors associated with institutional and community support [48,49] for the viability of decentralisation in desalination supply need to be integrated into the decision making process. Integrated frameworks such as the LCA–LC approach used in this study can provide insight into the environmental and economic trade-offs and co-benefits of planning decisions. However, additional research is needed to incorporate stakeholder engagement into project assessments.

4. Conclusion

Large seawater desalination plants designed to serve metropolitan water supply systems often need to be located far from population centres. Although such plants benefit from economies of scale in their construction, they must rely on long distance pipeline infrastructure in order to deliver their treated water to consumers. The preceding sections of this paper have demonstrated a method for examining the trade-offs between desalination plant economies of scale, water transportation costs and environmental impacts. This was done by comparing the environmental and economic performances of different scaled desalination systems using site-specific data for Perth, WA, where significant investment in water transport infrastructure would be required to connect a large, centralised plant to the city's water supply network. Using LCA and LC analyses, we tested this centralised base-case scenario against two alternative scenarios involving integration of an equivalent capacity of smaller plants into the water demand area.

Our results suggest that decentralisation of metropolitan desalination capacity has the potential to significantly reduce the environmental impacts of the system and supply water at a lower per-unit cost when compared to the centralised approach. Contribution analysis revealed that, although economies of scale resulted in lower environmental impacts from the desalination plant construction and operation phases, these savings were outweighed by the environmental impacts associated with the operation of the water transfer mains required to connect the large plant to the network. LC modelling found that plant decentralisation would deliver desalinated water to consumers at a lower per-unit cost than the centralised plant, mainly due to the avoidance of transfer main construction costs. As this result was based on site-specific assumptions we do not claim that it has general applicability; indeed, we found that if the water main length assumption was reduced by 54% in the case study while holding all other assumptions constant, the centralised scenario outperformed the decentralised scenario on the basis of cost. We conclude that the environmental and/or economic assessment of a desalination-based urban water supply system can be strongly influenced by inclusion or exclusion of the water pipeline network in the boundary of analysis. More generally, for planning the optimum scale and geographical distribution of desalination-based urban water supply systems, it is important that life cycle environmental and/or economic assessment methods be incorporated with spatial and temporal case study data that encompass as much of the supply chain as possible.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2015.08.012.

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5.3. Chapter summary and link to next chapter

This chapter addresses the forth research question, namely**, what are the influences of SWRO desalination plants size and location on the life cycle environmental and economic performances of a desalinated water supply system.** A framework for investigating the optimum geographical scale for desalinated water planning using spatial and temporal case study data (e.g. land availability, water demand, and existing pipeline network) coupled with hybrid LCA and LC analyses were developed. The method's applicability was tested using data for the northern corridor of Perth, Western Australia. Comparative life cycle assessment and economic analyses of desalination supply system for three geographical scales were conducted: a centralised scenario and two alternative decentralised scenarios. The main implication of this study for the water supply industry is that, when building any new seawater desalination plant for a metropolitan area, it is essential to optimise with respect to the size and location of the plant, rather than to simply follow the conventional engineering wisdom of 'bigger is better'. Given that desalination plants size and location has significant influence on the life cycle environmental performance of desalination plants supply chain, this decision is incorporated as a key decision variable in desalination supply chain decision model developed in chapter 6. Moreover, the results of this chapter use as input data to the model in chapter 6.

5.4. Appendix B: Paper 4 supporting information

Table S 1 Centralized scenario plant size and water delivery distances between the plant and suburbs of water demand

Plants ID	Design capacity (m^3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
1	320,000	3.20E+05	0.14	Seabird	City Beach	99
					Claremont (WA)	110
					Cottesloe	108
					Floreat	100
					Mosman Park - Peppermint Grove	110
					Nedlands - Dalkeith - Crawley	108
					Swanbourne - Mount Claremont	107
					Craigie - Beldon	82
					Currambine - Kinross	74
					Duncraig	87
					Heathridge - Connolly	78
					Hillarys	81
					Iluka - Burns Beach	79
					Mullaloo - Kallaroo	79
					Ocean Reef	75
					Padbury	85
					Sorrento - Marmion	84
					Innaloo - Doubleview	94
					Karrinyup - Gwelup - Carine	94
					Osborne Park Industrial	96
					Scarborough	97
					Stirling - Osborne Park	93
					Trigg - North Beach - Watermans Bay	93
					Wembley Downs - Churchlands -	102

Plants ID	Design capacity (m^3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
					Woodlands	
					Butler - Merriwa - Ridgewood	68
					Clarkson	67
					Mindarie - Quinns Rocks - Jindalee	68
					Yanchep	56

Table S 2 Cluster scale 1, Decentralized scenario plant sizes and water delivery distances between the plants and suburbs water demand

Plants ID	Design capacity (m^3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
2	65,000	4.87E+03	0.006	Swanbourne - Mount Claremont	City Beach	9
					Claremont (WA)	2
					Cottesloe	2
					Floreat	8
					Mosman Park - Peppermint Grove	4
					Nedlands - Dalkeith - Crawley	3
					Swanbourne - Mount Claremont	0
3	110,000	6.12E+03	0.008	Iluka - Burns Beach	Craigie - Beldon	4
					Currambine - Kinross	6
					Duncraig	10
					Heathridge - Connolly	5
					Hillarys	3
					Iluka - Burns Beach	0
					Mullaloo - Kallaroo	1
					Ocean Reef	4

Plants ID	Design capacity (m^3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
					Padbury	6
					Sorrento - Marmion	7
4	80,000	4.84E+03	0.006	Scarborough	Innaloo - Doubleview	4
					Karrinyup - Gwelup - Carine	5
					Osborne Park Industrial	6
					Scarborough	0
					Stirling - Osborne Park	7
					Trigg - North Beach - Watermans Bay	4
					Wembley Downs - Churchlands - Woodlands	1
5	65,000	5.11E+04	0.004	Mindarie - Quinns Rocks - Jindalee	Butler - Merriwa - Ridgewood	5
					Clarkson	3
					Mindarie - Quinns Rocks - Jindalee	0
					Yanchep	2

Table S 3 Cluster scale 2, Decentralized scenario plant sizes and water delivery distances between the plants and suburbs of water demand

Plants ID	Design capacity (m3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
6	20,000	2.28E+03	0.006	Swanbourne - Mount Claremont	City Beach	9
					Floreat	8
					Swanbourne	0
7	50,000	2.59E+03	0.009	Cottesloe	Claremont (WA)	3
					Cottesloe	0

Plants ID	Design capacity (m3/day)	Catchment (hectares)	Electricity use in distribution (kwh/m^3)	Plant location	Service area	Distribution distance, km
					Mosman Park	3
					Nedlands - Dalkeith - Crawley	5
8	20,000	1.23E+03	0.003	Hillarys	Hillarys	0
					Padbury	4
				Iluka - Burns Beach	Currambine - Kinross	6
9	20,000	1.18E+03	0.006		Iluka - Burns Beach	0
10	20,000	1.30E+03	0.003	Mullaloo Kallaroo	Craigie - Beldon	4
					Mullaloo - Kallaroo	0
11	20,000	1.19E+03	0.003	Ocean Reef	Ocean Reef	0
					Heathridge - Connolly	4
12	20,000	1.22E+03	0.0039	Sorrento Marmion	Sorrento - Marmion	0
					Duncraig	4
13	50,000	2.85E+03	0.009	Scarborough	Innaloo - Doubleview	4
					Osborne Park Industrial	6
					Scarborough	0
					Stirling - Osborne Park	7
					Wembley Downs - Churchlands - Woodlands	11
14	35,000	1.98E+03	0.003	Trigg North Beach - Watermans Bay	Trigg - North Beach - Watermans Bay	0
					Karrinyup - Gwelup - Carine	2
15	20,000	1.08E+03	0.000	Clarkson	Clarkson	0
				Mindarie Quinns Rocks - Jindalee	Butler - Merriwa - Ridgewood	5
16	45,000	5.00E+04	0.01		Mindarie - Quinns Rocks - Jindalee	0
					Yanchep	23

Table S4 Summary of design parameters for Reverse Osmosis processes, the scenarios were designed and optimized with system design software ROSA [59] and ERI power model [60]

Plants ID	Design capacity (m^3/day)	Number of trains	Number of PV	RO element	Number of PE	PE Element	HPP pump efficiency (%)	Circulation pump efficiency (%)	RO specific energy (kWh/m3)
8-12, 6, 15	20,000	4	50	SW30HRLE-370/34i	4	PX-260	77	79	2.85
14	35,000	6	50	SW30HRLE-370/34i	4	PX-260	77	79	2.85
16	45,000	6	70	SW30HRLE-370/34i	8	PX-260	80	82	2.75
7,13	50,000	6	80	SW30HRLE-370/34i	8	PX-260	80	82	2.75
2,5	65,000	6	100	SW30HRLE-370/34i	8	PX-260	80	82	2.75
4	80,000	6	125	SW30HRLE-400i	8	PX-Q300	81	83	2.65
3	110,000	12	180	SW30HRLE-400i	8	PX-Q301	81	83	2.65
1	320,000	24	125	SW30HRLE-400i	8	PX-Q302	81	83	2.65

Table S5 Scenarios configuration, input flows to the systems

	Scenarios characteristics	Inputs to EIO-LCA	
Name	Plants ID	Treatment plant building, facilities & storage tank (2002 US$/m3)	Transfer main capital cost (2002 US$/m3)
Decentralised scenario, cluster scale 2	6	3.89E-01	NA
	7	4.43E-01	NA
	8	4.43E-01	NA
	9	4.43E-01	NA
	10	4.43E-01	NA
	11	4.43E-01	NA
	12	4.43E-01	NA
	13	3.89E-01	NA
	14	4.04E-01	NA
	15	4.43E-01	NA
	16	3.89E-01	NA
Decentralised scenario, cluster scale 1	2	3.85E-01	NA
	3	3.45E-01	NA
	4	3.78E-01	NA
	5	3.85E-01	NA
Centralised scenario	1	2.40E-01	2.27E-01

Table S6 Uncertainty factors, square of the geometric standard deviation and probability distribution for inventory data

Inventory data	Uncertainty factors of reliability (U_1)[1]	Uncertainty factors of completeness (U_2)[1]	Uncertainty temporal (U_3)[1] factors of correlation	Uncertainty factors of geographical correlation (U_4)[1]	Uncertainty factors of further technological correlation (U_5)[1]	Square of the geometric standard deviation (σ_g^2)[2]	Probability distribution type[3]
Membrane materials (Pre-treatment)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Membrane material (RO)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Chemical use (intake & Pre-treatment)	1.00	1.00	1.03	1.00	1.00	1.03	lognormal
Chemical Use (RO)	1.00	1.00	1.03	1.00	1.00	1.03	lognormal
Plastic waste	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Construction	1.54	1.00	1.19	1.04	1.00	1.60	lognormal
Electricity (Intake)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Electricity (Pre-treatment)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Electricity (RO)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Electricity (distribution)	1.61	1.00	1.00	1.00	1.00	1.61	lognormal
Material Transportation	1.00	1.00	1.00	1.00	1.00	1.00	lognormal

[1] The uncertainty factors for each inventory flows were estimated by using default uncertainty factors applied together with Pedigree matrix. This is a qualitative method and the method assumptions and descriptions could be found in literature [57] .

[2] The square of the geometric standard deviation (95% interval- SD_{g95}) is calculated with the following formula [56]:

$$SD_{g95} := \sigma_g^2 = \exp\left(\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2}\right)$$

[3] Lognormal distribution was applied on life cycle inventory data. Lognormal is a realistic approximation for the variability in fate and effect factors than normal distribution due to the fact that emissions measurement are not show negative values [56].

CHAPTER 6. MULTI-PERIOD MIXED INTEGER LINEAR OPTIMISATION FRAMEWORK FOR LIFE CYCLE ASSESSMENT –BASED DESALINATION SUPPLY SYSTEM PLANNING

6.1. Attribution

Maedeh P. Shahabi wrote all sections of this paper, developed mathematical optimisation model, designing scenarios and conducted all data analysis. Adam McHugh, Martin Anda and Goen Ho acted as co-supervisors and read various drafts of papers and provided feedback regarding the scope of the study, scenario development and sensitivity analysis, results, discussion and developed mathematical model.

Maedeh P.Shahabi:+80%

6.2. Paper 5: Planning sustainable seawater desalination infrastructure for metropolitan areas

6.2.1. Abstract

A recent trend in seawater desalination, which has significantly contributed freshwater supply to coastal metropolitan areas around the globe, is investment in large, high-capacity plants. Desalination plants enjoy economies of scale in their construction phase. However, large plants often need to be located far from population centres due to lack of reserved land for their siting and so must rely on long distance pipeline infrastructure to deliver their treated water to consumers. Construction and operation of pipeline infrastructure comes with economic costs and environmental impacts. We postulate that the lack of integration in planning of desalination supply systems and metropolitan land-use decisions leads to suboptimal economic and environmental outcomes. We present a quantitative framework for sustainable desalination planning in metropolitan areas which integrates the tools of mixed integer linear programming, life cycle assessment and Geographical Information System. The framework was tested for future desalination planning in the northern metropolitan area of Perth, Western Australia. Results indicate that if land could be reserved for accommodating future decentralised desalination plants in the area of water demand, the environmental and economic impacts associated with the supply system could be reduced by up to 26% when compared with those associated with a proposed centralised plant and pipeline solution.

6.2.2. Introduction

System thinking approach toward sustainable planning of desalination sourced water supply

The global capacity of desalination increased by 57% between 2008 and 2013 [61]. This trend is expected to continue because of increasing global population, diminishing traditional water resources and advances in membrane technology. Seawater desalination is a drought proof, indefinite water resource that contributes 59% of world desalination capacity [5]. The recent global trend in the desalination industry for metropolitan areas is planning for large scale desalination plants to fulfil up to 50 percent of a city's long term drinking water needs [6]. For example since 2006 in the Australian cities of Perth, Melbourne and Sydney, large desalination plants have been built to contribute 25%, 33% and 15% of drinking water needs of the respective metropolitan areas during drought [62]. This global trend is based on two factors: economies of scale and concern over water shortages in the context of increasing demand and climate change. These factors must be balanced against the energy intensive operation of the water distribution infrastructure associated with large centralised plants [63].

Policy makers and engineers need to make sure that the centralised planning of metropolitan desalination supply creates an overall benefit for the system rather than a burden shift between economic and environmental impact categories (i.e. private costs versus external costs) or between supply system life cycle stages (e.g. construction phase versus operational phase). Developing desalination planning strategies for metropolitan areas requires a systems approach that covers the environmental and economic life cycle at a high level of detail.

Sustainable desalination planning

Since 1952 mathematical modelling techniques have been employed as a planning tool in the water resources sector [32]. Optimization models address water allocation planning [32-42], water supply infrastructure planning [8, 43-50], regional wastewater allocation planning [50] and regional wastewater infrastructure planning [39, 51-53]. Among this literature there are a few decision making tools which were designed for large investments in seawater desalination [8, 45, 54]. In 2011, Liu, Konstantopoulou [45] developed a Mixed Integer Linear Programming (MILP) model to manage water resources including desalinated seawater, wastewater and reclaimed water. The integrated optimization model was applied to two Greek islands and the optimal water management decisions, including the location of desalination, wastewater treatment, and reclamation plants and their connected networks were obtained by minimising the annualised total capital and operating costs. In 2013, Al-Nory, Brodsky [8] proposed a mathematical optimisation model to trace the plant location, technology type, capacity, operational considerations, distribution network structure and capacity. GHG emissions data of different desalination technology types were integrated into the model to include environmental considerations in the decision-making process, but they did not consider the GHG emissions associated with pipeline system construction and operation. In 2014, Saif and Almansoori [54] proposed multi-period MILP modelling to optimise the retrofit of a water desalination supply system. The model key decision variables include new facility location and capacity expansion of water desalination supply chain infrastructure assets. The cost of CO_2 emissions was included in the analysis but cost of construction phase emissions were excluded. Moreover in both works [8] and [54], there is lack of detailed environmental impacts data for various sizes of desalination plant and pipeline infrastructure, which could lead to underestimation of burdens associated smaller sized plants and pipelines if impacts data are derived from , given average impacts to decrease with plant scale.

To the best of our knowledge, there are no optimisation models for desalination planning that consider simultaneously life cycle costs and a range of life cycle environmental impacts for various sizes of desalination plant and pipeline infrastructure. The recent work of [8] only considered aggregated GHG data without considering trade-offs that may exist between different environmental impact indicators. Moreover, the previous optimisation models for desalination planning [8, 54] were designed for regional desalination planning and did not incorporate land-use constraints, while for metropolitan desalination planning, land-use constraints do need to be incorporated into the model.

Research scope

The present work goes beyond previous research by Al-Nory, Brodsky [8] and Saif and Almansoori [54] in several respects. Firstly, a developed multi-period MILP model can optimise the desalinated water supply based on both life cycle costs and environmental impacts, allowing for their trade-offs to be explored. Secondly, the model incorporates full LCA, considering the whole life cycle of various sized of plants and pipelines, from construction to operation. The model, combined with scenario analysis, can help identify the influence of land-use, economic and environmental policies on the optimal decision.

In this present study we integrate common tools of MILP, Geographic Information System (GIS) and LCA in order to develop a framework for compatible land, environmental impacts and desalinated water supply in metropolitan areas. This framework could be used to bring decision-makers from the different disciplines of water, environment and land use planning to work together and tackle the problem of seawater desalination planning in metropolitan areas.

6.2.3. Method

To achieve sustainable desalination planning within existing metropolitan areas, we developed a quantitative framework by integrating the MILP optimisation model, the LCA (quantifying environmental impacts) model, levelised cost (quantifying economic cost) model and GIS (spatial-temporal case study data) databases (Figure 1).

First, we quantified the spatial-temporal desalinated water demand forecast, and land that is potentially available in the case study area using GIS. Second, we quantified life cycle costs and environmental impacts for various sizes of plant and pipeline considering site specific energy, land

and capital costs and also environmental emissions intensities. Third, we developed the MILP optimisation model and used results of the two previous steps to obtain the model parameters and constants. Lastly, we applied the integrated model to the case study. The model can be optimised on economic or environmental objectives based on decision makers' preferences and for each objective (environmental and economic policies implication) an optimal solution can be obtained for the case study. We used the model to investigate to what extent sustainable desalination planning can be met under different land-use constraints in metropolitan areas (land use policies implication), economic policies (WACC implication) and environmental policies (water efficiency saving).

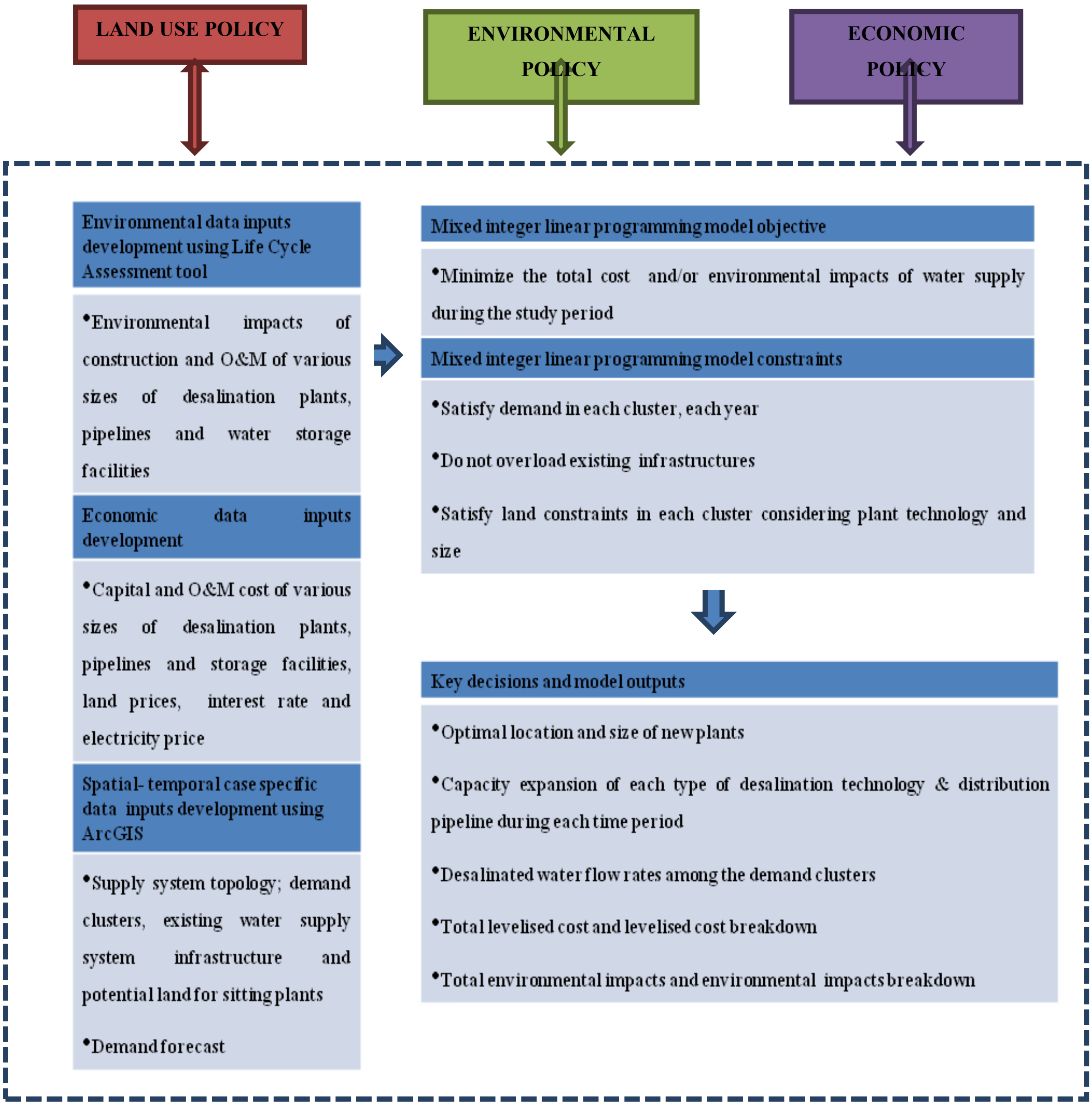

Figure 6-1 The quantitative optimization framework. The framework integrates desalination supply system planning (mixed integer linear programming tool), environmental impact assessment (Life cycle assessment tool), economic cost analysis (discounted expenditure flow method) with land use, environmental and economic policies scenarios.

The MILP optimisation

In general, a MILP optimisation problem can be formulated as:

Minimize $\quad f(x, y)$

Subject to $h(x, y) = b$

$g(x, y) \leq 0$

Where $x \in \mathbb{R}$

$y \in \mathbb{Z}$

Where $f(x,y)$ denotes an objective function, $h(x, y)$ is a vector of equality constraint terms, b is a vector of real constants, $g(x, y)$ is a vector of inequality constraint terms, x is a continuous variable, $\mathbb{R}$ is the set of all real numbers, y is an integer or binary variable and $\mathbb{Z}$ is the set of all integers. The MILP model developed for the present study includes four major types of constraints. They are the water demand balance constraints, plant capacity constraints, land constraints and pipeline network constraints which are described in equations (S1) – (S11) in the supporting information. Eq. (S12) – (S32) in the supporting information define the one economic indicator and ten environmental impact indicators which are the objective functions to be optimized.

The MILP model developed for the present study facilitates optimization based on either economic costs or environmental impacts objective functions. Environmental impacts and economic costs were accounted on a life cycle basis considering the desalinated water supply system over the planning time horizon. The economic objective function was the present cost of the water supply system over the planning horizon. In addition to the present cost of the system, the levelised cost (LC) of water was also calculated. LC is an engineering economics metric that is used for measuring and comparing the total unit cost of alternative projects that deliver similar products. It is the real price at which a long term contract would need to be negotiated in order for a project to breakeven in net present value (NPV) terms.

The environmental objectives were defined in terms of the life cycle environmental impacts. In addition to the total life cycle environmental impacts of the system, the environmental impacts per functional unit (levelised environmental impacts, LE) were calculated for each system. In LCA study, the same functional unit - 'supplying one cubic meter of desalinated water to the defined demand area’ - was chosen for each scenario to make them comparable.

The MILP model was coded into and solved using the GAMS 24.3.1 solver CPLEX 12.6 [24]. The model contains 1,698 constraints and 9,923 variables of which 4,320 are binary. The MILP model structure is fully documented in the supporting information. In the following sections only those features and parameters that are central to understanding the main results are presented.

Case study context and scenarios description

Perth is Australia’s fourth most populous (~2 million people) city, located on the west coast of Western Australia, and has a Mediterranean-type climate, dominated by wet winters and relatively dry summers [64]. In response to recent climate change (reduced rainfall) [65] and population growth, two large SWRO desalination plants have been built since 2006, increasing drinking water supply to the region by 145 GL per annum. There will be significant demand for additional, 'drought-proof' sources of water over the next decade. A new 100 GL per annum SWRO desalination plant, the Northern Seawater Desalination Plant (NSDP), has been proposed to support future urban expansion in the northern corridor of Perth and to replace a loss of capacity in the groundwater water supply system resulting from a persistent trend in reduced rainfall in its catchment area [65, 66]. The land constraint in the metropolitan area means that, if capacity is to be provided by a single large plant, it will need to be located far from the water demand nodes. For the NSDP, there will need to be 68 kilometres of trunk main constructed to connect the plant to the existing water distribution system.

In our analysis, the NSDP is considered to be the **Business As Usual (BAU) scenario**. We employed our MILP model to develop two alternative, optimal scenarios to supply the northern corridor of Perth future desalinated water and to compare them with the **BAU scenario**. The two optimal scenarios assumed flexible land-use zoning change in which vacant land for long term urban land development projects can be considered for accommodating desalination plants after going through the process of land use change. In the **Optimal cost scenario**, a single-objective optimisation model was solved by considering the total NPV of the water supply system as the model objective while in the **Optimal GWP scenario**, the model was solved by considering the total life cycle

GHG emissions of the desalinated water supply system as the optimisation objective.

Desalination plants processes

In line with our previous study [67], two common process configurations are considered for SWRO desalination plants: open intake and beach well intake. In an open intake process configuration, a seawater reverse osmosis (SWRO) desalination plant draws seawater through an open intake, which is then subjected to membrane pre-treatment prior to RO. In a beach well intake process configuration, feedwater is extracted from the subsurface, which is then passes through a simplified cartridge filtration process prior to RO. Beach well intake process configurations were considered for plants with a design capacity of 35,000 m^3/day and electricity use per functional unit of 3 kWh/m^3; for technical and economic reasons [68-70], plants employing beach well intake facilities for extracting seawater do not generally exceed this size. Beach well intake applications were constrained to those of sites which are located no further than 500 m from the coast line. Open intake was considered for SWRO plants between design capacity of 35,000 m^3/day and 320,000 m^3/day. 20 sizes were included in our analysis with electricity use per functional unit ranges between 3.00 kwh/m^3 to 3.20 kwh/m^3 based on the plants sizes. Open intake process configuration was considered for both inland and coastal sites. Desalination plants primary data for electricity use, membrane use, landfill and brine disposal and material transportation were obtained from our previous studies [63, 67].

Model parameters and constants

Water demand forecast

We defined five clusters (water demand zones) for the study area consisting of 28 suburbs in Perth northern metropolitan area (Figure 2). Currently, the drinking water demand in these five clusters is supplied from groundwater resources located in east of the area. We assumed that by building the new desalination source, the current and future demand in these clusters will be provided from desalination source water. The sizes of the clusters were selected based on our previous preliminary study for Perth desalination supply. The demand in each cluster was determined by multiplying the projected average annual water demand per capita by a Perth population forecast to the year 2035. Perth's water use per capita was adopted from a published document by the Water Corporation of Western Australia [66]. Clusters' current populations and rates of population growth were obtained from the Australian Bureau of Statistics' various online databases [71-73]. The data analysis was conducted in ArcGIS 10 and exported to Excel to integrate with the MILP model. For all three scenarios, water demand assumptions were identical. Detailed water demand forecasts for the five clusters from 2015-2034 are documented in Table S1, supporting information.

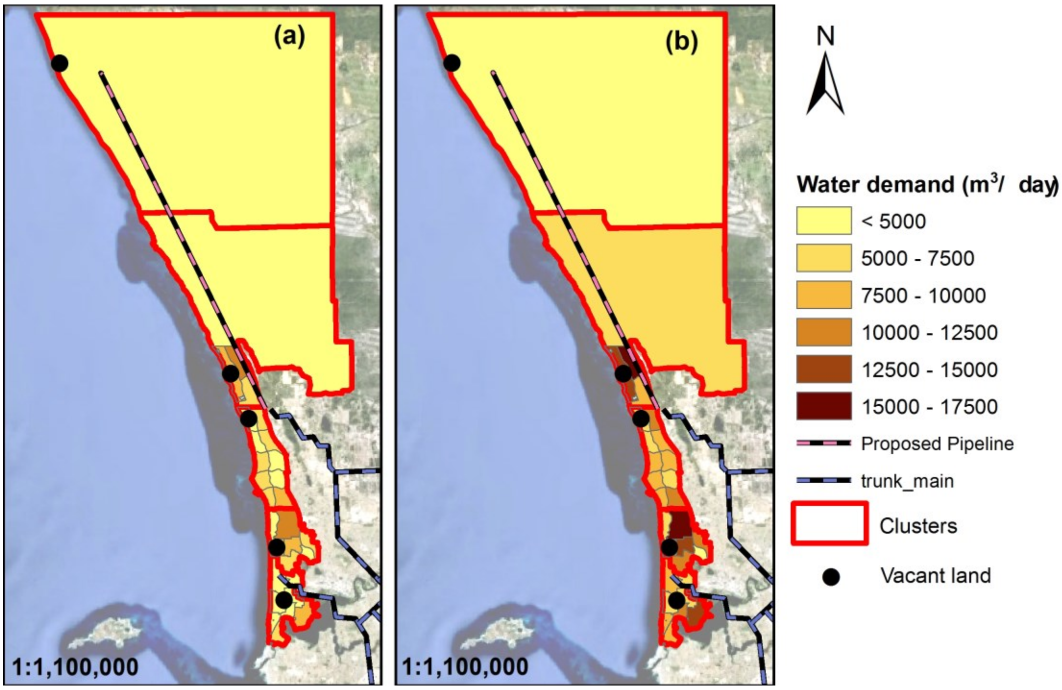

Figure 6-2 Clusters boundaries, vacant land for sitting the plants, existing infrastructure map and spatial temporal water demand a) Spatial water demand map in year 2015 b) Spatial water demand map in 2034.

Land-use, existing distribution system constraint

The plant location of the BAU scenario was taken from the proposed scenario in "Water forever: toward climate resilience" prepared by the Water Corporation of Western Australia [28]. At the time of writing, the land considered for accommodating the plant in this scenario was zoned for industrial land use. The two other scenarios assumed possible land use zoning change, in which long term urban land development projects with anticipated commencement timeframes of greater than ten years could be considered for accommodating desalination plants. Northern metropolitan spatial plans [74] were employed for selecting plants sites. The size of each plant, which could be built in each cluster, was constrained by the availability of suitable land. Inland and coastal sites sizes and their distances from the coastline are documented in Table S2, supporting information.

Existing distribution system constraints need to be incorporated into the model. For example the flow from cluster 2 to cluster 1 is possible but the flow from cluster 1 to cluster 2 is not possible due to size constraint in existing trunk main. Another constraint is associated with integration cost of clusters to the existing supply system. Existing distribution system constraint obtained for the case study is documented in Table S3, supporting information.

Cost data and levelised cost analysis

All capital and operational and maintenance (O&M) costs, for different desalination plant sizes and process configurations, water storage tanks and distribution pipelines except electricity, land and labour, were adopted from the literature [58] and adjusted to 2015 Australian dollars (AU$) using exchange rates obtained from the Reserve Bank of Australia database [75] and producer price indices obtained from the Australian Bureau of Statistics database [76]. Land requirements in hectares for plant sizes and process configurations were obtained from [58]. The unit cost of land was assumed to be AU$300/$m^2$. Electricity consumption requirements for different plant sizes and process configurations was based on documented conceptual designs [67]. The wholesale electricity price of AU$143 per MWh was obtained from [77]. The number of full time staff required for routine O&M of different sized plants and process configurations were adopted from literature [58]. Labour cost was calculated based on a 2015 wage of AU$68,203 per year [78]. The real Weighted Average Cost of Capital (WACC) of 6.62% proposed by the Western Australian Water Corporation was selected for the LC analysis [79]. All plants, their connected storage tanks and trunk mains were assumed to be constructed during the 2014 financial year, with production commencing the following year. Plant capacity factors were assumed to be less than 85%. The capital and O&M cost data for 20 plant sizes, 20 seawater intake facilities sizes and 12 desalinated water pipeline sizes are documented in Table S4&S5, supporting information.

Environmental data and functional unit

The life cycle environmental impacts for 12 different plant sizes and process configurations, 12 seawater transportation pipeline sizes, and 10 desalinated water pipeline sizes were estimated using life cycle assessment (LCA), following the CML 2001 impact assessment method [80]. Australian high voltage electricity data [81] was used for modelling onsite energy consumption in plants and pipeline distribution systems. Grid mix electricity supply and also transmission losses were included in the database. The detailed methodology and LCA results for estimating the environmental impacts of pipeline and plants using hybrid-LCA is described in [67]. In total, ten impact categories were included in the model: Abiotic Depletion Potential (ADP) which relates to extraction of minerals and fossil fuels, Acidification Potential (AP) which relates to emissions of acidifying substances to air, Eutrophication Potential (EP) referring to emissions of nutrients to air, water and soil, Global Warming Potential (GWP) which relates to GHG emissions, Ozone Layer Depletion (ODP) which relates to emissions of specific ozone depleting gases, Human Toxicity Potential (HTP) related to impacts of toxic substances on the human environment, Fresh Water Aquatic Eco-toxicity (FWAE), Marine Aquatic Eco-Toxicity Potential (MAETP) and Terrestrial Eco-toxicity Potential (TETP) which are related to emissions of toxic substances to air, water and soil and Photochemical Oxidation Potential (POCP) which relates emissions of reactive substances harmful to human health and ecosystems. In the LCA study, the same functional unit – 'supplying one cubic meter of desalinated water to the defined demand area of all clusters' - was chosen for all scenarios to make them comparable.

6.2.4. Results

The results provided in this section refer to single-objective optimisation performed on ten environmental objectives and one economic objective. We also compare the results from the MILP model (optimal scenarios) with the BAU reference scenario described in section 2.1. It should be noted that the scenario analysis is illustrative of a possible pathway for desalination planning in Perth, WA and is not intended to provide a full strategic analysis, although this could be achieved if desired using the present methodology by applying it to a more extensive set of scenarios.

Comparison of BAU scenario with cost and GWP optimal scenarios

Table 1 shows the design configuration and the results of LC and GWP breakdown for the BAU, optimal cost and optimal GWP scenarios. The scenarios differed in terms of proposed locations and capacities of plants/pipelines (Table 1).

The **BAU scenario** and the **Optimal cost scenario** were shown to have substantially different economic performances. In the **BAU scenario**, building and facilities construction formed the most significant component of the total cost (44% of total). Seawater and brine transportation pipeline construction cost constituted the second largest portion of the total cost (31%). The variable plant O&M cost component followed with an 18% share of the total cost, while the other components contributed between 2% and 4%. For the **Optimal cost scenario**, building and facilities construction costs constituted the most significant component of the total cost, this being equal to 71% throughout the whole examined period. Variable plants O&M costs, which include treatment electricity cost, was the next largest portion of the total cost, equal to 23% of the total cost, and the other components contributed between 1% and 3%. The LC of **Optimal cost scenario** was 26% lower LC than for the **BAU scenario**. The cost associated with building and facilities construction was higher in the **Optimal cost scenario** compared with the **BAU scenario** due to economies of scale. However this saving was outweighed by the cost of constructing the transfer main.

The **BAU scenario** and the **Optimal GWP scenario** were reasonably different with respect to their environmental performances. In the **BAU**

scenario, plant O&M again comprised the most significant component of GWP, but only 68% of the total. Not surprisingly, water distribution network electricity use constituted the second largest portion of the total GWP (24%). The other components followed with smaller percentages (less than 3%). In the **Optimal GWP scenario**, plant O&M comprised the most significant component of the total GWP (92%). Building and facilities construction GWP impact constituted the second largest share (6%). The other components contributed less than 1% each. Overall the **Optimal GWP scenario** resulted in a 26% lower GWP than the **BAU scenario**. Surprisingly, GHG emissions associated with seawater and brine pumping electricity use were higher in the **Optimal GWP scenario** when compared with the **BAU scenario**. For the case study investigated in this paper, this was due to the closest suitable land to the coast that could accommodate the cluster 2 plant being 4.5 km inland. However the high GWP associated with the water distribution network electricity use in the **BAU scenario** still dominated the GHG emissions associated with seawater and brine pumping electricity use across both scenarios.

The **Optimal cost scenario** and **Optimal GWP scenario** were reasonably different regarding the capacity expansion trends. The overall pattern of the results provided in Table 1 indicates that optimal cost is obtained by incremental capacity expansion of desalination plants while optimal GWP is obtained by one-step capacity expansion. Expansion of desalination capacity via an incremental and staged capital expenditure program reduces interest costs. However, multi-staged construction of desalination plants increases environmental impacts associated with electricity use in water distribution network in the early years of supply system operation when limited number of plants serve the total demand area.

In general the MILP model shows that decentralised multi-staged planning provides better outcomes than centralised planning. However, the construction of decentralised plants may require politically or legally difficult land-use zoning changes. Planning requires foresight to reserve land use for this purpose.

Table 6-1 Design configuration, levelised cost and GWP breakdown of scenarios for supplying 1 m^3 water of desalinated water

		Optimal Scenarios	
Planning decisions	**BAU scenario**	**Optimal cost scenario**	**Optimal GWP scenario**
SWRO desalination plants capacity construction or expansion details: Plant location/year of construction or expansion/capacity (m^3/day) /process configuration	Cluster 5/year 1/320,000/Open intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake
		Cluster 1/year 18/35,000/Open intake	Cluster 1/year 2/35,000/Open intake
		Cluster 3/year 4/50,000/Open intake	Cluster 2/year 1/35,000/Open intake
		Cluster 3/year 11/65,000/Open intake	Cluster 3/year 1/140,000/Open intake
		Cluster 4/year 1/140,000/Open intake	Cluster 4/year 1/80,000/Open intake
LC component (AU\$/m^3)			
Building and facilities construction (capex)	1.74	2.05	2.58
Transfer main pipeline construction (capex)	1.24	-	-
Seawater and brine transportation pipeline construction (capex)	0.01	0.07	0.13
Variable O&M (opex)	0.70	0.67	0.67
Fixed O&M (opex)	0.070	0.06	0.08
Water distribution network electricity use (opex)	0.17	0.03	0.01
Seawater and brine pumping electricity use (opex)	0.002	0.01	0.01
LC (total)/Relative differences with BAU scenario	3.94	2.90/26%	3.48/12%
Cumulative 20-year GWP component (g $CO_{2.e}$/m^3)			
Building and facilities construction (construction)	153	230	230
Transfer main pipeline construction (construction)	111	0	0
Seawater & brine pipeline construction (construction)	1	9	11
O&M (operation)	3320	3288	3288
Water distribution network electricity use (operation)	1140	189	41
Seawater and brine pumping electricity use (operation)	122	51	17
GWP (total)/ Relative differences with BAU scenario	4847	3767/22%	3588/26%

The impact of model objective selection

Figure 3 depicts all the solutions obtained by solving eleven single-objective problems. The horizontal axis of Figure 3 represents the different objectives, while the vertical axis shows the normalised value of LC and environmental indicators attained for each solution in each objective. The normalisation has been performed by dividing the values of the indicators by the maximum obtained over all solutions.

In general, optimising the model on the cost objective resulted in higher environmental impacts than when the model was optimised on the related environmental indicator. The converse was also true, cost was higher when the model optimised for the environmental indicator. For example, by optimising for MAETP, normalised value for environmental indicators of ADP, AP, EP, GWP, HTP, FAETP and POCP were 1% higher, cost was 18% higher and ODP was 8% higher compared with the case when the model was optimised on their related indicators.

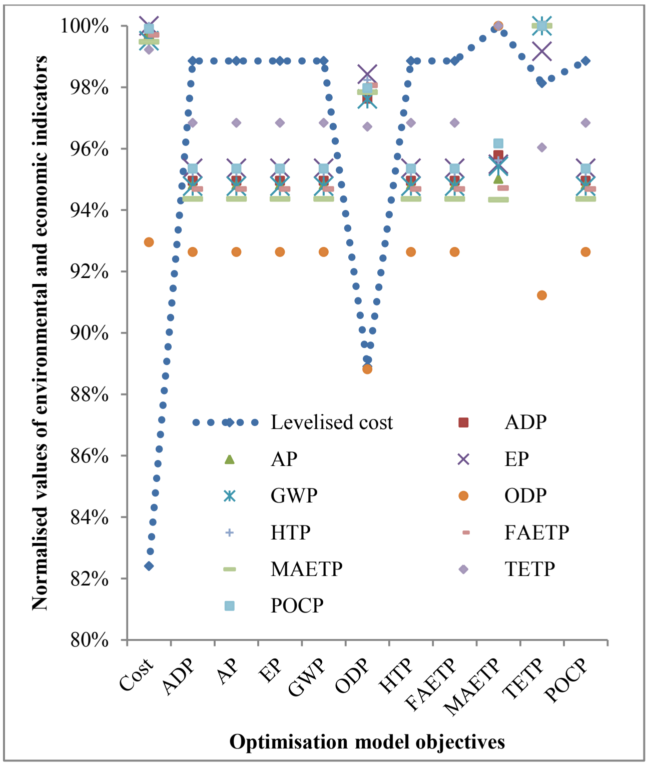

Figure 6-3 Optimal solutions relative cumulative environmental and economic performance obtained by solving the eleven single-objective problems. The maximum values per functional unit (m^3) obtained for each impact category are: LC:3.52$, ADP: 2.69E-02 kg Sb, AP: 2.22E-02 kg SO_2, EP: 1.42E-03 kg PO_4, GWP: 3.79E+00 kg CO_2, ODP: 2.11E-07 kg CFC-11, HTP: 1.03E-01 kg 1,4-DB, FAETP: 8.31E-01 kg 1,4-DB, MAETP: 2.66E+03 kg 1,4-DB, TETP: 1.98E-03 kg 1,4-DB, POCP: 8.82E-04 kg C_2H_4.

As seen in Figure 3, optimization on any of the environmental indicator led to reductions in the remaining environmental indicators compared to Optimal cost scenario. However, there is an exception for ODP, which increased by 7% when optimising on cost and increased by 10% when optimising for MAETP. This was due to ODP environmental impacts mainly occurring during the construction phase, while non-ODP environmental impacts mainly occurred during the operational phase.

Detailed contribution analysis of the desalination supply chain for the same case study in our previous research [67] showed that, while all environmental impacts are highly influenced by plants' O&M, ODP is an exception and is mostly a function of plant construction. Similarly, most the project costs were incurred during the construction phase rather than the operational phase. The details of each optimal solution capacity expansion plan are provided in the supporting information, Table S6.

In short, the ADP, AP, EP, GWP, HTP, FAETP, MAETP and POCP objectives were found to be highly correlated, which suggest co benefits exists in optimising on these environmental impacts. Future optimisation analysis for this desalination supply chain could be simplified by optimising on one of these environmental objectives.

Costs and environmental impacts trade-offs

Figure 4 depicts the trade-offs between total cost and environmental impact categories, in which each point represents a different solution entailing specific planning decisions. For each point in the graph, we solved a single-objective problem to minimise the environmental impact associated with one of the impact categories while we constraint the value of cost for the point. The total net cost and environmental impact values have been normalised by dividing each of them by the maximum value attained for it among all the Pareto solutions.

As observed in figure 4, for maximally environmental effective systems, the total system cost increases sharply. For example, 4% reduction in life cycle GWP could be achieved for a 14% increase in cost. Most of the additional cost above the optimal cost scenario is due to interest cost associated with one-step capacity expansion in optimal environmental scenarios. The trade-off relation could be observed between cost and environmental impacts. The only exception is ODP which shows both trade-off and synergy relationships based on the cost range. These results illustrate that to avoid suboptimal solutions for desalination supply chain, considering range of economic and environmental objectives is necessary. However, it is worth noting that trade-off or synergy between different environmental and economic objectives is site specific.

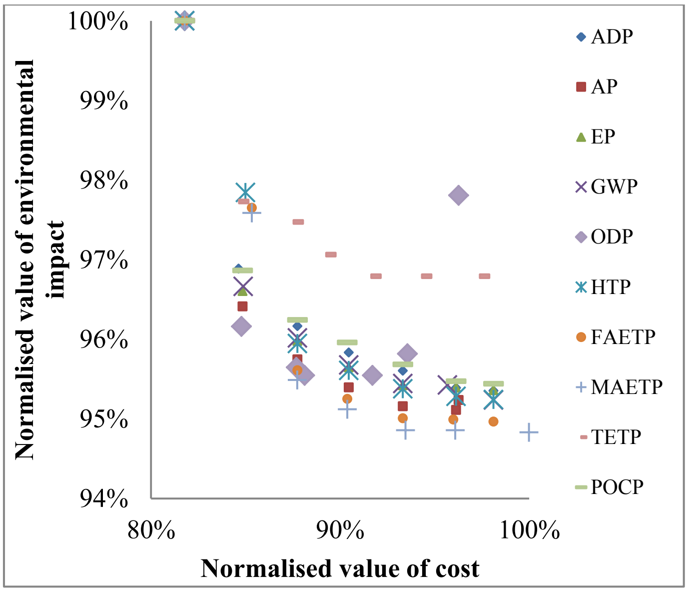

Figure 6-4 Pareto sets corresponding to each environmental impact category being optimised.

The impact of land use, water demand, electricity supply model and rate of return assumptions

Additional scenarios were analysed to understand the effects on the supply system's economic and environmental performance of modifying land use, WACC, and water demand assumptions.

As mentioned in method section, optimal reference scenarios assumed 100% possible land use change, in which urban land of long term development projects (with anticipated commencement of development of greater than ten years), could be considered for accommodating desalination plants after going through land use zoning change processes. As a form of sensitivity testing, i.e. in order to see the impacts of the land decisions on the scenarios economic and environmental performances, we conceptualised two more scenarios in which only 25% and 50% of land areas could be released for accommodating plants. Differences between normalised impacts of the optimal cost and BAU scenarios under three land use change scenarios across the eleven environmental and economic impact categories are presented in Figure 5a. Results suggest that a better environmental performance is obtained through the planning for Optimal cost scenario in lieu of the BAU scenario under all the different land use change strategies among all economic and environmental indicators, except for ODP. This is due to ODP impacts mainly occurring during the construction phase in the decentralised planning scenarios.

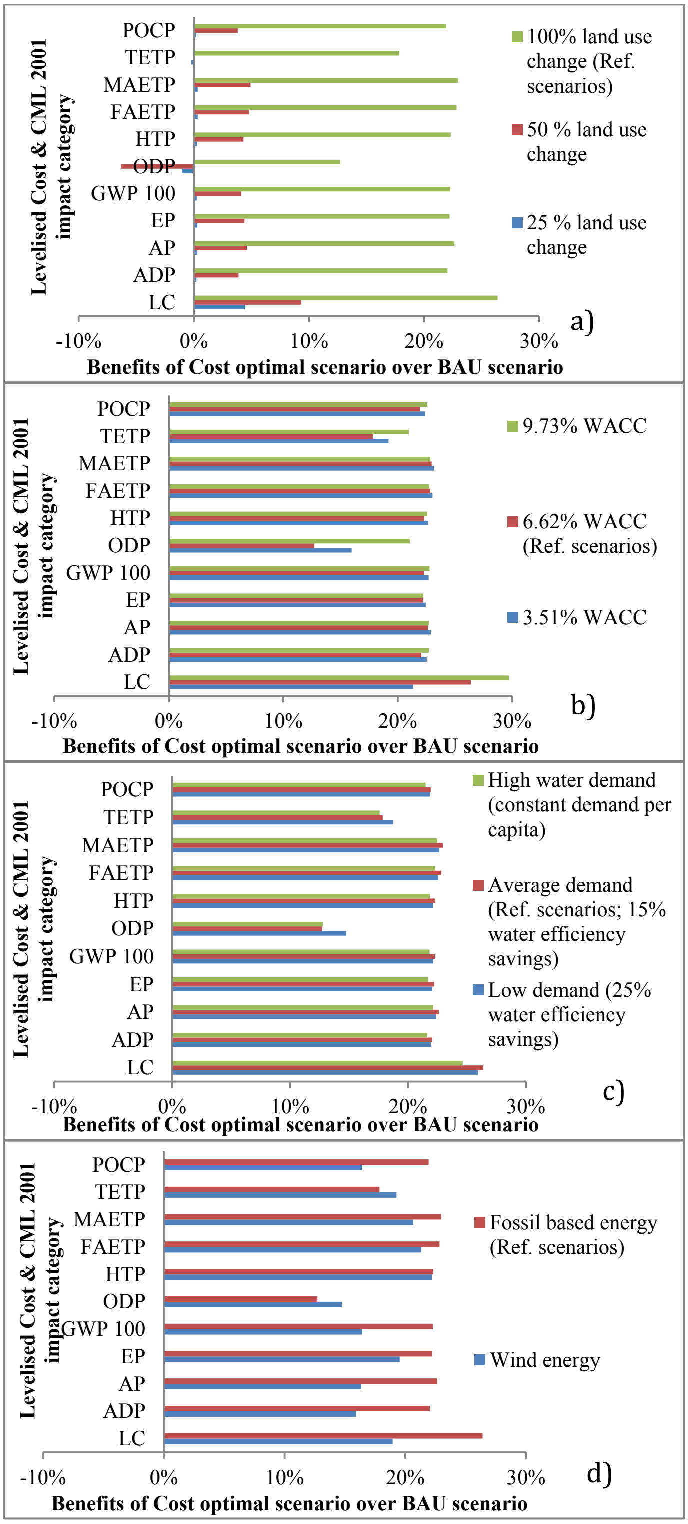

Figure 6-5 Environmental and economic benefits of Optimal cost scenario over BAU scenario in percentage terms for three different land use change implementations (a) for three different Weighted Average Cost of Capital (b) for three different water efficiency savings per capita in 20 years (c) for two different electricity supply model (d).

As mentioned in Method section above, reference scenarios were modelled with the WACC of 6.65% proposed by Water Corporation. As a sensitivity test, we also modelled the WACC of 3.51% estimated by the Western Australian Economic Regulation Authority (ERA) [79] and, for symmetry, a WACC of 9.73% (which we arrived at by adding the difference between the ERA WACC and the Water Corporation proposed WACC to the ERA proposed WACC). Differences between normalised impacts of the Optimal cost and BAU scenarios under three WACC across the eleven environmental and economic impact categories are presented in Figure 5b. Results for all the economic and environmental indicators suggested that a better environmental performance would be obtained by planning for the optimal cost scenario in lieu of the BAU scenario under all WACC assumptions tested.

As mentioned in Method section above, reference scenarios modelled an annual water demand per capita of 135 m^3 in 2015, and reducing by 15% over 20 years due to water efficiency savings. As a sensitivity test, we also modelled water efficiency savings of 25% and 0% over 20 years. Differences between the normalised impacts of the optimal cost and BAU scenarios under the three water saving strategies across the eleven environmental and economic impact categories are presented in Figure 5c. The results show that economic and environmental performance is generally robust over the tested range of demand.

The Australian electricity mix was chosen to model the onsite electricity use in the reference scenarios LCA analysis as described in section 2.4.4.

The Australian energy mix consists of approximately 70% coal, 14% natural gas and the remaining 7% is derived from several sources including wind and photovoltaic. As a sensitivity test, we modelled the plants and distribution systems electricity supply with wind electricity. Differences between the normalised impacts of the optimal cost and BAU scenarios under the two electricity supply model across the eleven environmental and economic impact categories are presented in Figure 5d. The results show that economic and environmental benefits of BAU scenario over cost optimal scenario are generally robust to electricity supply model.

In summary, these sensitivity analysis results suggest that the better environmental and economic performance of decentralised planning over centralised planning is highly sensitive to the proportion of land that can be made available for sitting the plants, but is highly resilient to changes in WACC, electricity supply model and water demand over a range of reasonable assumptions.

6.2.5. Discussion

Two key insights were obtained through this work. The first was that integrated analysis tools can assist in the planning of more sustainable desalination plants in metropolitan areas. For a metropolitan area with scarce land for the siting of desalination plants, the factors of supply system configuration, land-use patterns, environmental impacts and economic costs are highly inter-related and planners should treat them as such rather than considering each separately. Secondly, acknowledging the integrated nature of desalination supply system planning, system costs, environmental impacts and land-use patterns opens up a wide range of planning concerns in the water and wastewater sectors (mainly those associated with water and wastewater distribution energy intensity). These can be assessed through our developed integrated framework. The framework gives the option of identifying conflicting objectives and co-benefits.

It should be noted that the scenarios for desalination planning in Perth, WA are merely explorative. Decentralisation can be a potential strategy to reduce environmental and economic impacts: for Perth northern metropolitan area with population density of 568 people per km^2 in 2015, decentralisation of desalination supply system could reduce environmental and economic impacts by up to 26% and 22% respectively. The framework allows for optimum desalination planning based on the decision maker's selected objective – environmental impact or project costs - under different land-use, environmental and economic policies scenarios. With these, we can trace the implications of various assumptions for future supply system configuration, environmental impacts and economic costs. The transparency and flexibility of the framework allows analysts from different disciplines to test the scenarios quantitatively, so as to understand potential planning implications.

The prevailing "wisdom" is that economies of scale benefits large centralised plants. However, the results of the analysis indicate that may not be a case for some case studies considering the complexities of accommodating the plants, land and capacity constraints, infrastructure requirements and demand patterns. This shows the importance of testing the decentralised supply system for any new desalination plants as part of the planning process in order to avoid the economic and environmental impacts of the supply system. The land constraint exists in the Perth case study, is likely to be applicable to any existing developed coastal cities worldwide.

Future studies could employ the proposed framework for assessing onsite wastewater options, rainwater tanks and other potential decentralised water supply alternatives in metropolitan areas. Integrating renewable energy use assumptions technologies, and desalinated water demand uncertainties associated with climate change patterns into the framework could be the subject of future studies.

6.3. Chapter summary and link to conclusion

This chapter addresses the fifth research question, namely**, Does application of the quantitative framework in desalination planning facilitate improved environmental and economic performance of the supply chain compared with Business as usual practises.** In this chapter a Multi-period mixed integer linear optimisation framework for life cycle assessment –based desalination supply system planning was developed. The model was used to analyse the economic and environmental impacts and trade-offs for alternative planning scenarios. The framework used life cycle assessment and a levelised cost model to quantify and compare the supply chain environmental and economic impacts for a range of planning scenarios. The framework incorporated a mixed integer linear programming model to determine optimal planning decisions such as water capacity expansion of each type of desalination technology over a planning horizon, and optimal locations of new desalination plants while considering interdependencies among water distribution and treatment processes. The framework was tested for future seawater reverse osmosis desalination planning in the northern metropolitan area of Perth, Western Australia over the next 20 years.

Mathematical model constants and parameters obtained from chapters 2, 3, 4, & 5. The size of clusters selected based on preliminary assessment in chapter 5.

Results indicated that, a decentralised desalination supply system with small and medium-sized SWRO plants integrated into the Perth metropolitan area could achieve 20% lower environmental and economic impact, when compared to a centralised supply system with a large desalination plant located far from final demand. Improving seawater quality by introducing beach well intake - a mature intake technology for smaller-sized plants - could further promote the decentralised supply system environmental and economic performance. Additional scenarios were analysed to understand the impacts of land use, economic and environmental policies implications on the supply system's economic and environmental performance. The results suggest that the better environmental and economic performance of decentralised planning over centralised planning is highly sensitive to the proportion of land that can be made available for sitting the plants through land use change, but is highly resilient to changes in WACC, electricity supply model and water demand.

The quantitative framework proposed in this chapter allows for optimum desalination planning based on the decision maker's selected objective – environmental impact or project costs - under different land-use, environmental and economic policies scenarios. With these, we can trace the implications of various assumptions for future supply system configuration, environmental impacts and economic costs. The transparency and flexibility of the framework allows analysts from different disciplines to test the scenarios quantitatively, so as to understand potential planning implications.

6.4. Appendix C: Paper 5 supporting information

Nomenclature

Indices

i,j	Cluster
k	plant size
p	pipe size
t	time period
b	plant process
e	environmental impact category

Sets

I	set of clusters
Le	set of allowed links I,j for water flow
K	Set of discrete points of the capacity for the desalination plants
P	Set of discrete points of the capacity for the pipelines
T	Set of time periods
B	Set of plant processes
E	Set of environmental impact categories

Parameters

$D_{i,t}$	Daily demand of desalinated water at cluster i during time period t (m^3/day)
$AK_{b,k}$	Design capacity of plant with process b at capacity breakpoint k (m^3/day)
cap_b	Maximum capacity factor of plant with process b (%)
$A^{max}_{i,b}$	Size of the largest plant with process b which could be built in cluster i (m^3/day)
PLQ_p	Flow rate of water in pipe of type p (m^3/day)
$envswt_{e,b,k}$	Construction environmental impact of seawater pipeline for plant with technology b at capacity k (impact category
$envo_{b,e}$	O&M environmental impacts of process b (impact category e unit/m^3)
$swcap_{b,k}$	Capital cost of seawater pipeline for plant with capacity k and process b ($/km)
$pcap_{b,k}$	Capital cost of plant with capacity k and process b ($)
plc_p	Capital cost of water pipeline for pipe of type p ($/km)
r	Discount rate
clt	Construction lead time for seawater pipeline/plant/water pipeline (year)
pfc_b	Unit fixed O&M cost for plant with technology b ($/m3)
ele	Unit electricity cost ($/kWh)
pvo_b	Unit variable O&M cost for plant with technology b ($/$m^3$)

Continous variables

$P_{i,b,t}$	Daily production volume of plant with process b at cluster i during time period t (m^3/day)
$Q_{i,j,t}$	Daily flow of water from cluster i to cluster j during time period t (m^3/day)
$A_{i,b,t}$	Total design capacity of plant with process b at cluster i during time period t (m^3/day)
$AX_{i,b,t}$	Design capacity expansion of plant with process b at cluster i during time period t (m^3/day)
$QC_{i,j,t}$	Total capacity of pipeline from cluster i to cluster j during time period t (m^3/day)
$QX_{i,b,t}$	Total capacity expansion of pipeline from cluster i to cluster j during time period t (m^3/day)
$f_{1,e}$	Total environmental impacts over the planning time horizon, objective (impact category e unit)
f_2	Total net present cost over the planning time horizon, objective ($)
CE_e	Construction environmental impacts (impact category e unit)
OE_e	O&M environmental impacts (impact category e unit)
CX	Net present capital cost over the planning time horizon ($)
OX	Net present variable O&M cost over the planning time horizon ($)
FX	Net present fixed O&M cost over the planning time horizon ($)

	e unit/km)		
coa_i	Seawater pumping distance for cluster i (km)	LC	Levelised cost ($/m^3)
$envc_{e,b,k}$	Construction environmental impact of plant with technology b at capacity k (impact category e)	LCC	Levelised capital cost ($/m^3)
$trandc_{i,j}$	Pipeline construction length from cluster i to j (km)	LOC	Levelised operational costs ($/m^3)
$envpl_{e,p}$	Construction environmental impact of water pipeline for pipe of type p (impact category e unit/km)	LE	Levelised environmental impacts (impact category e unit /m^3)
DP_t	Duration of period t (days/year)	LCE	Levelised construction environmental impacts (impact category e unit /m^3)
μ_p	Efficiency of pump (%)	LOE	Levelised O&M environmental impacts (impact category e unit /m^3)
μ_m	Efficiency of motor (%)	**Binary variables**	
p	Density of water (kg/m^3)	$S_{i,b,t,k}$	1 if plant capacity expansion occurs during time t at capacity k from technology b at cluster i; 0 otherwise
g	Standard gravity (m/s^2)	$E_{i,b,t}$	1 if plant capacity expansion occurs during time t from technology b at cluster i; 0 otherwise
ΔH	Head loss of water in pipeline (m/km)	$YP_{i,j,t,p}$	1 if pipe capacity expansion from type p occurs during time t from cluster i to cluster j; 0 otherwise
$H_{i,j}$	Pumping elevation from cluster i to j (m)	$YX_{i,j,t}$	1 if pipe capacity expansion occurs during time t from cluster i to cluster j; 0 otherwise
rr	Plant recovery ratio (%)		
$envele_e$	Unit electricity environmental impact (impact category e unit/ kWh)		

The Mixed Integer Linear Programming optimisation problem

The overall capacity expansion planning problem of a desalinated supply system taking life cycle environmental impacts into consideration is formulated as a MILP problem, involving the constraint functions (S1-S11), environmental objective functions (S12-S18), and the economic objective functions (S19-S26).

Model constraints

Water balance

The desalinated water demand in cluster i, at each year t *($D_{i,t}$)* is equal to the water production from desalination technology b at cluster i during year t *($P_{i,b,t}$)*, plus all incoming desalinated water flows from other clusters j to cluster i during year t *($Q_{j,i,t}$)*, minus all out going desalinated water flows from cluster i to other clusters j during year t *($Q_{i,j,t}$)*.

$$D_{i,t} = \sum_{b} P_{i,b,t} + \sum_{j} Q_{j,i,t} - \sum_{j} Q_{i,j,t} \qquad \forall i, b, t, \{i, j\} \mathcal{E} Le \qquad \text{(S1)}$$

Plant capacities

The capacity of a plant in cluster *i* from desalination technology *b* during time period *t* is equal to the capacity of a plant in cluster *i* from technology *b* from the previous time period *t-1*, plus the capacity expansion in cluster *i* from technology *b* during time period *t*. The capacity expansion of every technology within every desalination plant can be selected from discrete values with *k* elements. All the above statements are formulated with the following equations:

$$A_{i,b,t} = A_{i,b,t-1} + AX_{i,b,t} \ \forall i, b, t \qquad \text{(S2)}$$

$$AX_{i,b,t} = \sum_{k} AK_{b,k}.S_{i,b,t,k} \qquad \forall i,b,t \tag{S3}$$

$S_{i,b,t,k}$ is a binary variable, and is only activated when the capacity expansion *k* with technology *b* will occur at cluster i during time period t.

$$E_{i,b,t} = \sum_{k} S_{i,b,t,k} \qquad \forall i,b,t \tag{S4}$$

It is assumed that at most one capacity expansion from technology b can occur at a cluster *i* during each time period t.

$$\sum_{b} E_{i,b,t} \leq 1 \qquad \forall i,t \tag{S5}$$

Plant capacity constraint

The capacity factor of a desalination plant is the amount of water that it produces over a period divided by the design capacity over the period. This set of constraints relates to plant operation. In each year, the produced water from a plant can not exceed its design capacity multiplied by the maximum capacity factor of the plant.

$$P_{i,b,y,t} \leq A_{i,b,t} \,.\, cap_{b} \qquad \forall i,b,y,t \tag{S6}$$

Land constraint

This set of constraints refers to the size of the largest plant which could be built in each cluster. The plant size in cluster i from technology b in any time period *t* can not exceed the maximum size which could be built in the cluster i.

$$A_{i,b}^{max} \leq A_{i,b,t} \tag{S7}$$

Pipeline network

The capacity of a pipeline network from cluster i to cluster j during time period t is equal to the capacity of a pipeline from cluster i to cluster j from time period t-1, plus the capacity expansion from cluster i to cluster j available in period t. The capacity expansion value of pipeline can be selected from discrete values with k elements in any time period t. All the above statements are formulated with the following equations:

$$QC_{i,j,t} = QC_{i,j,t-1} + QX_{i,j,t} \qquad \forall i, j, t, \{i, j\} \mathcal{E} Le \tag{S8}$$

$$QX_{i,j,t} = \sum_{p} PLQ_p . YP_{i,j,t,p} \qquad \forall i,j,t,p,\{i,j\}\mathcal{E}Le \tag{S9}$$

$YP_{\ i,j,t,p}$ is a binary variable, and is only activated when the capacity expansion p occurs from cluster i to j during time period t.

$$YX_{i,j,t} = \sum_p YP_{i,j,t,p} \qquad \forall i,j,t,p,\{i,j\}\mathcal{E}Le \tag{S10}$$

Moreover, in the pipeline network, at most one pipe type p can be selected for each link during time period t:

$$\sum_{p,t} YP_{i,j,p,y,t} \leq 1 \quad \forall i,j,t,p,\{i,j\}\mathcal{E}Le \tag{S11}$$

Objective functions

Environmental objectives

The environmental objectives are defined as the life cycle environmental impacts which accounts for the seawater transportation pipeline, desalination plant and treated water pipeline construction and operation phases. The life cycle environmental impacts are estimated using life cycle assessment (LCA) following the CML 2001 impact assessment method [25]. In total ten impact categories are included in the model: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Layer Depletion (ODP), Human Toxicity Potential (HTP), Fresh Water Aquatic Eco-toxicity (FWAE), Marine Aquatic Eco-Toxicity Potential (MAETP), Terrestrial Eco-toxicity Potential (TETP) and Photochemical Oxidation Potential (POCP). The environmental objective functions are given by equation S12.

$$f_{1,e} = CE_e^{SeaWater} + CE_e^{Plant} + CE_e^{Distribution} + OE_e^{SeaWater} + OE_e^{Plant} + OE_e^{Distribution} \tag{S12}$$

The components of the $f_{1,e}$ are described in detail below.

- **Construction environmental impacts** (CE_e) defines the construction environmental impacts associated with impact category *e.* It includes impacts of each newly-built and also the capacity expansion of seawater and brine transportation pipeline ($CE^{seawater}$), plant and storage tank (CE^{Plant}), and also newly-built water pipeline ($CE^{Distribution}$) which should be built to integrate a new plant to existing distribution system as given by the following equations:

$$CE_e^{Seawater} = \sum_i \sum_b \sum_t \sum_k envswt_{e,b,k} \,.\, coa_i . S_{i,b,t,k} . \ \forall i, b, t, k \tag{S13}$$

$$CE_e^{Plant} = \sum_i \sum_b \sum_t \sum_k envc_{e,b,k} \,.\, S_{i,b,t,k} . \forall i, b, t, k \tag{S14}$$

$$CE_e^{Distribution} = \sum_i \sum_j \sum_b \sum_t \sum_k trandc_{i,j} \, . \, YP_{i,j,t,p} . envpl_{e,p} \;\; \forall b, t, k, \{i, j\} \quad \text{(S15)}$$

- **Operational and maintenance environmental impacts** (OE_e) refers to the operation and maintenance environmental impacts associated with impact category *e*. OE_e includes environmental impacts associated with seawater pumping electricity use ($OE_e^{seawater}$), desalination plant all O&M (OE_e^{plant}), and treated water distribution pumping electricity use (OX_e^{pipe}) as given by the following equations:

$$OE^{Seawater} = \sum_i \sum_b \sum_t DP_t . \frac{1}{\mu_p . \mu_m} . p . g . \left(Coa_i . \Delta H + H_{i,j}\right) . envele_e \, . \left(PB_{i,b,t} / rr\right) \;\; \forall i, b, t \quad \text{(S16)}$$

$$OE^{Plant} = \sum_i \sum_b \sum_t DP_t . PB_{i,b,t} \, . \, envo_{b,e} \;\; \forall i, b, t \quad \text{(S17)}$$

$$OE^{Distribution} = \sum_i \sum_j \sum_t DP_t . \frac{1}{\mu_p . \mu_m} . p . g . \left(trand_{i,j} . \Delta H + H_{i,j}\right) . envele_e \, . \, Q_{i,j,t} \;\; \forall t, \{i, j\} \mathcal{E} Le \quad \text{(S18)}$$

Economic objective

The economic objective function is the net present cost of the water supply system over the planning horizon, and is given by equation S19.

$$f_2 = CX^{SeaWater} + CX^{Plant} + CX^{Distribution} + OX^{SeaWater} + FX^{Plant} + OX^{Plant} + OX^{Distribution} \qquad \text{(S19)}$$

The components of the f_2 are described in detail below.

- **Capital cost** (*CX*) includes all the capital investments cost of each newly-built and also the capacity expansion of seawater and the brine transportation pipeline ($CX^{seawater}$), plant and storage tank (CX^{plant}), and also the treated water pipeline (CX^{pipe}), which should be built to integrate a new plant to existing distribution system. Future costs are discounted at rate (r) over the construction lead-time (clt) as given by the following equations.

$$CX^{Seawater} = \sum_i \sum_b \sum_t \sum_k swcap_{b,k} \,.\, coa_i . S_{i,b,t,k} . \left(\frac{1}{(1+r)^{t-clt^{SeaWater}}}\right) \; \forall i,b,t,k \qquad \text{(S20)}$$

$$CX^{Plant} = \sum_i \sum_b \sum_t \sum_k pcap_{b,k} \,.\, S_{i,b,t,k} . \left(\frac{1}{(1+r)^{t-clt^{Plant}}}\right) \; \forall i,b,t,k \qquad \text{(S21)}$$

$$CX^{Distribution} = \sum_i \sum_j \sum_b \sum_t \sum_k trandc_{i,j} \,.\, YP_{i,j,t,p} . plc_p \left(\frac{1}{(1+r)^{t-clt^{Distribution}}}\right) \; \forall b,t,k,\{i,j\} \qquad \text{(S22)}$$

- **Fixed operational and maintenance costs** (*FX*) refers to the cost required for operation and maintenance of the system that is not related to the amount of water produced by the supply system. FX is considered for the desalination plant with future costs discounted at rate (*r*):

$$FX^{Plant} = \sum_i \sum_b \sum_t DP_t . pfc_b \, . A_{i,b,t} . \left(\frac{1}{(1+r)^t}\right) \;\; \forall i, b, t \tag{S23}$$

- **Variable operational and maintenance costs** (*OX*) refers to the costs required for annual operation and maintenance and is directly related to the amount of water produced by each system component. In this study OX includes seawater pumping electricity costs ($OX^{seawater}$), all variable O&M costs associated with th desalination plant (OX^{plant}), and treated water distribution pumping electricity cost (OX^{pipe}) taking into account an interest rate (*r*) as given by the following equations:

$$OX^{Seawater} = \sum_i \sum_b \sum_t DP_t . \frac{1}{\mu_p . \mu_m} . p . g . \left(Coa_i . \Delta H + H_{i,j}\right) . ele \, . (PB_{i,b,t} / rr) . \left(\frac{1}{(1+r)^t}\right) \;\; \forall i, b, t \tag{S24}$$

$$OX^{Plant} = \sum_i \sum_b \sum_t DP_t . PB_{i,b,t} \, . pvo_b . \left(\frac{1}{(1+r)^t}\right) \;\; \forall i, b, t \tag{S25}$$

$$OX^{Distribution} = \sum_i \sum_j \sum_t DP_t . \frac{1}{\mu_p . \mu_m} . p . g . \left(trand_{i,j} . \Delta H + H_{i,j}\right) . ele \, . Q_{i,j,t} . \left(\frac{1}{(1+r)^t}\right) \;\; \forall t, \{i, j\} \mathcal{E} Le \tag{S26}$$

Environmental impacts per functional unit

In LCA study, the same functional unit is chosen for each scenario to make them comparable, this being supplying one cubic meter of desalinated water to the defined demand area of all clusters. In addition to the total life cycle environmental impacts of the systems (objective function $f_{1,\,e}$), the environmental impacts per functional unit (LE) were calculated for each system. We partitioned LE into two components, construction phase environmental impacts per functional unit (LCE) and O&M environmental impacts per functional unit (LOE), such that:

$$LE_e = LCE_e + LOE_e \qquad \text{(S27)}$$

$$LCE_e = \frac{CE_e{}^{SeaWater} + CE_e{}^{plant} + CE_e{}^{distribution}}{\sum_{i,b,t} P_{i,b,t}} \qquad \forall i, b, t \qquad \text{(S28)}$$

$$LOE_e = \frac{OE_e{}^{SeaWater} + OE_e{}^{plant} + OE_e{}^{distribution}}{\sum_{i,b,t} P_{i,b,t}} \qquad \forall i, b, t \qquad \text{(S29)}$$

Levelised cost

In addition to the net present cost of the system (objective function f_2), the levelised cost (LC) of water was calculated for each system. LC is an engineering economics metric that is used for measuring and comparing the total unit cost of alternative projects that deliver similar products. It is the real price at which a long term contract would need to be negotiated in order for a project to breakeven in net present value (NPV) terms. We partition LC into two components; levelised capital cost (LCC) and levelised operational costs (LOC) as given by the following equations:

$$LC = LCC + LOC \quad \text{(S30)}$$

$$LCC = \frac{CX^{SeaWater} + CX^{plant} + CX^{distribution}}{\sum_{i,b,t} \frac{P_{i,b,t}}{(1+r)^t}} \quad \forall i, b, t \quad \text{(S31)}$$

$$LOC = \frac{OX^{SeaWater} + OX^{plant} + FX^{plant} + OX^{distribution}}{\sum_{i,b,t} \frac{P_{i,b,t}}{(1+r)^t}} \quad \forall i, b, t \quad \text{(S32)}$$

Table S 1 Spatial-Temporal estimated water demands for the case studies; D i,t

	Demand (m^3/year)				
Year	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
2015	1.05E+07	1.67E+07	1.35E+07	9.41E+06	1.05E+07
2016	1.09E+07	1.74E+07	1.40E+07	9.76E+06	1.09E+07
2017	1.13E+07	1.80E+07	1.45E+07	1.01E+07	1.13E+07
2018	1.17E+07	1.87E+07	1.50E+07	1.05E+07	1.17E+07
2019	1.22E+07	1.94E+07	1.56E+07	1.09E+07	1.22E+07
2020	1.26E+07	2.01E+07	1.62E+07	1.13E+07	1.26E+07
2021	1.31E+07	2.08E+07	1.68E+07	1.17E+07	1.31E+07
2022	1.35E+07	2.16E+07	1.74E+07	1.21E+07	1.35E+07
2023	1.40E+07	2.24E+07	1.80E+07	1.26E+07	1.40E+07
2024	1.46E+07	2.32E+07	1.87E+07	1.30E+07	1.46E+07
2025	1.50E+07	2.40E+07	1.94E+07	1.35E+07	1.50E+07
2026	1.56E+07	2.49E+07	2.01E+07	1.40E+07	1.56E+07
2027	1.62E+07	2.58E+07	2.08E+07	1.45E+07	1.62E+07
2028	1.68E+07	2.68E+07	2.16E+07	1.50E+07	1.68E+07
2029	1.74E+07	2.77E+07	2.23E+07	1.56E+07	1.74E+07
2030	1.80E+07	2.87E+07	2.31E+07	1.61E+07	1.80E+07
2031	1.87E+07	2.98E+07	2.40E+07	1.67E+07	1.87E+07
2032	1.94E+07	3.08E+07	2.48E+07	1.73E+07	1.94E+07
2033	2.01E+07	3.19E+07	2.57E+07	1.79E+07	2.01E+07
2034	2.08E+07	3.31E+07	2.66E+07	1.86E+07	2.08E+07
Total	3.02E+08	4.82E+08	3.88E+08	2.71E+08	3.02E+08

Table S 2 Desalination plants capacity constraint based on land use; $A^{max}_{i,b}$, coa_i

Capacity constraint for beach well(m^3/day)/capacity constraint for open intake(m^3/day)/distance from coastline(km)				
Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
35000/35000/0.5	0/35000/4.5	0/150000/3	0/150000/1	35000/320000/0.5

Table S 3 Pipeline construction lengths, allowed pumping distances and elevation between two clusters; trandc i,j , trand i,j, H i,j

Construction length (km)/Pumping distance (km)/elevation(m)					
	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Cluster 1	0/-/0	0/31/0	0/11/0	0/39/0	0/103/0
Cluster 2	0/-/0	0/-/0	0/20/0	0/12/0	0/75/0
Cluster 3	0/-/0	0/-/0	0/-/0	0/29/0	0/93/0
Cluster 4	0/-/0	0/-/0	0/-/0	0/-/0	68/68/0
Cluster 5	0/-/0	0/-/0	0/-/0	68/-/0	0/-/0

Table S 4 Cost data for different sizes of SWRO plants

Design capacity(m^3/day)	Plant intake type	Plant Capital cost ($)	Seawater pipeline construction ($/km)	Plant variable O&M ($/$m^3$)	Plant fixed O&M ($/$m^3$)
3.50E+04	Beach well	2.06E+08	4.83E+06	0.5	0.1
3.50E+04	Open intake	2.31E+08	4.83E+06	0.7	0.04
5.00E+04	Open intake	3.19E+08	5.52E+06	0.7	0.04
6.50E+04	Open intake	4.08E+08	6.21E+06	0.7	0.04
8.00E+04	Open intake	4.94E+08	6.90E+06	0.7	0.04
9.50E+04	Open intake	5.71E+08	7.59E+06	0.7	0.04
1.10E+05	Open intake	6.19E+08	8.62E+06	0.7	0.04
1.25E+05	Open intake	6.88E+08	8.62E+06	0.7	0.04
1.40E+05	Open intake	7.39E+08	9.31E+06	0.7	0.04

Design capacity(m^3/day)	Plant intake type	Plant Capital cost ($)	Seawater pipeline construction ($/km)	Plant variable O&M ($/$m^3$)	Plant fixed O&M ($/$m^3$)
1.55E+05	Open intake	7.67E+08	9.66E+06	0.7	0.04
1.70E+05	Open intake	8.18E+08	1.00E+07	0.7	0.04
1.85E+05	Open intake	8.9E+08	1.03E+07	0.7	0.04
2.00E+05	Open intake	9.41E+08	1.07E+07	0.7	0.04
2.15E+05	Open intake	9.84E+08	1.10E+07	0.7	0.04
2.30E+05	Open intake	1.04E+09	1.14E+07	0.7	0.04
2.45E+05	Open intake	1.07E+09	1.19E+07	0.7	0.04
2.60E+05	Open intake	1.11E+09	1.24E+07	0.7	0.04
2.75E+05	Open intake	1.15E+09	1.29E+07	0.7	0.04
2.90E+05	Open intake	1.19E+09	1.35E+07	0.7	0.04
3.05E+05	Open intake	1.23E+09	1.40E+07	0.7	0.04
3.20E+05	Open intake	1.27E+09	1.45E+07	0.7	0.04

Table S 5 Cost and environmental data for different sizes of pipes

Pipe diameter (inch)	Capital cost ($)	ADP (kg Sb)	AP (kg SO_2)	EP (kg PO_4)	GWP (kg CO_2)	ODP (kg CFC-11)	HTP (kg 1,4-DB)	FAETP (kg 1,4-DB)	MAETP (kg 1,4-DB)	TETP (kg 1,4-DB)	POCP (kg C_2H_4)
48	1.80E+06	2.82E+03	6.57E+02	2.99E+01	3.18E+05	1.87E-01	5.30E+04	7.50E+03	7.92E+06	7.55E+02	9.16E+01
54	2.87E+06	4.51E+03	1.05E+03	4.79E+01	5.08E+05	2.99E-01	8.48E+04	1.20E+04	1.27E+07	1.21E+03	1.47E+02
66	3.23E+06	5.07E+03	1.18E+03	5.38E+01	5.72E+05	3.36E-01	9.54E+04	1.35E+04	1.43E+07	1.36E+03	1.65E+02
72	4.31E+06	6.76E+03	1.58E+03	7.18E+01	7.63E+05	4.48E-01	1.27E+05	1.80E+04	1.90E+07	1.81E+03	2.20E+02
70	5.03E+06	7.89E+03	1.84E+03	8.38E+01	8.90E+05	5.23E-01	1.48E+05	2.10E+04	2.22E+07	2.11E+03	2.57E+02
84	5.82E+06	9.13E+03	2.13E+03	9.69E+01	1.03E+06	6.05E-01	1.72E+05	2.43E+04	2.57E+07	2.45E+03	2.97E+02
90	6.47E+06	1.01E+04	2.36E+03	1.08E+02	1.14E+06	6.73E-01	1.91E+05	2.70E+04	2.85E+07	2.72E+03	3.30E+02
96	7.90E+06	1.24E+04	2.89E+03	1.32E+02	1.40E+06	8.22E-01	2.33E+05	3.30E+04	3.49E+07	3.32E+03	4.03E+02
102	8.62E+06	1.35E+04	3.15E+03	1.44E+02	1.53E+06	8.97E-01	2.54E+05	3.60E+04	3.80E+07	3.62E+03	4.40E+02
108	1.01E+07	1.58E+04	3.68E+03	1.68E+02	1.78E+06	1.05E+00	2.97E+05	4.20E+04	4.44E+07	4.23E+03	5.13E+02
120	1.15E+07	1.80E+04	4.20E+03	1.91E+02	2.03E+06	1.20E+00	3.39E+05	4.80E+04	5.07E+07	4.83E+03	5.86E+02
144	1.33E+07	2.09E+04	4.86E+03	2.21E+02	2.35E+06	1.38E+00	3.92E+05	5.55E+04	5.86E+07	5.59E+03	6.78E+02

Table S 6 SWRO desalination plants capacity expansion details for different optimisation solutions

Location/year of expansion/capacity (m^3/day) / process configuration								
Minimising on the ADP	Minimising on the AP	Minimising on the EP	Minimising on the ODP	Minimising on the HTP	Minimising on the FAETP	Minimising on the MAETP	Minimising on the TETP	Minimising on the POCP
Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake	Cluster 1/year 1/35,000/Beach well intake
Cluster 1/year 2/35,000/Open intake	Cluster 1/year 2/35,000/Open intake	Cluster 1/year 2/35,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 1/year 2/35,000/Open intake	Cluster 1/year 2/35,000/Open intake	Cluster 1/year 2/35,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 1/year 2/35,000/Open intake
Cluster 2/year 1/35,000/Open intake	Cluster 2/year 1/35,000/Open intake	Cluster 2/year 1/35,000/Open intake	Cluster 4/year 1/110,000/Open intake	Cluster 2/year 1/35,000/Open intake	Cluster 2/year 1/35,000/Open intake	Cluster 2/year 1/35,000/Open intake	Cluster 4/year 1/110,000/Open intake	Cluster 2/year 1/35,000/Open intake
Cluster 3/year 1/140,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 4/year 15/35,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 3/year 1/140,000/Open intake	Cluster 3/year 1/80,000/Open intake	Cluster 5/year 1/35,000/ Beach well intake	Cluster 3/year 1/140,000/Open intake
Cluster 4/year 1/80,000/Open intake	Cluster 4/year 1/80,000/Open intake	Cluster 4/year 1/80,000/Open intake	-	Cluster 4/year 1/80,000/Open intake	Cluster 4/year 1/80,000/Open intake	Cluster 3/year 3/35,000/Open intake	-	Cluster 4/year 1/80,000/Open intake
-	-	-	-	-	-	Cluster 3/year 12/35,000/Open intake	-	-
-	-	-	-	-	-	Cluster 4/year 1/35,000/Open intake	-	-
-	-	-	-	-	-	Cluster 4/year 3/35,000/ Open intake	-	-

CHAPTER 7. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

This thesis represents an attempt to develop a water desalination supply chain optimization life cycle framework to analyse the economic and environmental impacts and trade-offs for alternative desalination supply planning scenarios. It has been demonstrated that to optimise the desalination supply chain environmental impacts and costs, a range of engineering, geographical, and scientific techniques are necessary. The methods applied in this thesis included GIS data analysis (Chapters 4, 5& 6), mathematical optimisation (Chapters 6), life cycle assessment (Chapters 2, 3, 4, 5 & 6), economic analysis (Chapters 3, 4, 5 & 6), process design (Chapters 3, 4), data acquisition and management (Chapters 2, 3, 4 & 5), and uncertainty analysis (Chapters 3 & 5 and sensitivity analysis (Chapters 2, 3, 5 & 6). The methods applied in this thesis are essential in assessing desalination supply chain holistically. In this chapter, we aim to evaluate the main contributions arising from addressing the research objectives and also provide potential research directions for the future work.

7.1. Contributions resulting from the research

At the beginning of this thesis five objectives were defined to address the overall aims of the research (see Chapter1). A brief evaluation of the main contributions arising from addressing these objectives is summarised here to emphasise the value of this thesis.

- **Quantify and compare the life cycle environmental performance of SWRO desalination plant powered by renewable energy and fossil fuel based grid (Chapter 2)**

  This chapter provides the first reference to identify and quantify supply chain contributions to the overall environmental impact associated with renewable energy powered desalination plants. We uniquely developed an economic Input-Output LCI database for Australian economic sector of "Non-Residential Building Construction" to use in desalination plants construction phase LCA analysis. Results shows that Indirect GHG emissions due to the electricity consumption in the chemical manufacture contributes the lion's share of the life cycle emissions for the renewable energy powered desalination plants while in fossil fuel based grid powered plants the electricity use in the operational phase is found to be responsible for more than 92% of its GHG emissions.

  These LCA results show that regardless of desalination plants power supply model, any improvement in reverse osmosis process towards lower chemical use can be beneficial by reducing impacts associated with upstream chemical manufacturing (addressed in Chapter 3).

- **Quantify and compare the life cycle environmental and economic performance of SWRO desalination plant using beach well intake and open intake facilities for extracting feedwater (Chapter 3).**

In this chapter, LCA and LC framework was developed to determine the optimum SWRO intake and pre-treatment configuration in order to reduce the chemical and electricity use in the process. The proposed framework has been applied to compare two scenarios: an open intake scenario in which a seawater reverse osmosis (SWRO) desalination plant employs open intake and membrane pre-treatment prior to RO, and a beach well scenario in which feedwater is extracted from the subsurface using beach well intake and cartridge filtration prior to RO. Results show that under favourable hydro-geological conditions, SWRO plants combining a beach well intake with a simplified pre-treatment prior to RO can significantly reduce the environmental impacts of the system at a lower economic cost per unit of desalinated water when compared to a typical open intake and membrane pre-treatment SWRO plant configuration.

Generally, the LCA and LC results show the importance of planning for optimum intake technology as a potential strategy for reducing environmental and economic impacts of desalination supply chain.

- **Quantify and compare the GHG emissions of centralised and decentralised SWRO desalination options (Chapter 4).**

  In this chapter, two scenarios of centralised and decentralised desalination supply for Perth metropolitan area were compared for their life cycle GHG emissions. Results show that site specific parameters of plant size and location could significantly affect the environmental impact of SWRO desalination plants.

The GHG emissions accounting results in this chapter show that decentralised planning is a potential strategy for reducing GHG emissions of desalination supply chain. In the next chapter (Chapter 5), the analysis was progressed to the area of full LCA and economic analysis in order to investigate decentralisation impacts on the life cycle environmental and economic performance of desalination supply chain.

- **Quantify and compare the life cycle environmental and economic performance of centralised and decentralised SWRO desalination options (Chapter 5).**

  Chapter 5 demonstrated a LCA and LC method for examining the trade-off between desalination plant economies of scale and water transportation costs and environmental impacts. Our results suggest that decentralisation of metropolitan desalination capacity has the potential to significantly reduce the environmental impacts of the system and supply water at a lower per-unit cost when compared to the centralised approach.

  Generally, the results are evidence that for planning the optimum scale and geographical distribution of desalination-based urban water supply systems, it is important that life cycle environmental and/or economic assessment methods are incorporated with spatial and temporal case study data that encompass as much of the supply chain as possible. In the next chapter (Chapter 6), the LCA-LC framework developed in this chapter was progressed to integrating mathematical optimisation to the modelling in order to develop a framework for optimising desalination supply chain environmental impacts and costs as whole.

- **Multi-period mixed integer linear optimisation framework for life cycle assessment –based desalination supply system planning (Chapter 6)**

  Chapter 6 presented the first life cycle-based framework to optimize the desalination supply system. To minimize the net present cost or/and life cycle environmental impacts, a MILP model was developed to determine the process type, location and capacity of desalination plants and the distribution systems. The proposed model was successfully applied to Perth northern metropolitan area and used to investigate several land use, economic and environmental scenarios. The comparative study shows that the cost optimal scenario saves much in cost and environmental impacts for the case study.

7.2. Recommendations for future work

Given the interdisciplinary nature of this research some areas of investigation were beyond the scope of this thesis. In order to further improve the framework and also support the results associated with application of the framework, further research is required. These are summarised here with a brief explanation for each:

- **Regulatory challenges**

  In desalination supply, regulatory challenges and public support are identified as two critical factors to the initiation and success of the projects [82]. Generally new approaches to urban water supply such as the decentralisation approach proposed in this study have often been controversial and their success implies a need for creation of an enabling environment [83] that incorporates factors including government support, financing opportunities and socio-cultural acceptance [84]. While this study proposed a quantitative life cycle framework for assessment of decentralisation, other significants factors associated with institutional and community support [85, 86] for the viability of decentralisation in desalination supply need to be integrated in the decision making process. Additional research is needed to incorporate stakeholder engagement into the quantitative life cycle framework proposed in this thesis.

- **Uncertainty analysis**

  In this thesis, all chapters used sensitivity analysis as a tool to check the robustness of results to the case specific assumptions such as different energy supply model, spatial-temporal demand, and interest rate and land availability. Only Chapters 3 and 5 considered the LCA database uncertainty factors which were estimated using Pedigree matrix. The uncertainty analysis was tackled by Monte Carlo simulation. However, the uncertainty issues can also be considered in the mathematical optimization model. The possible uncertain factors could be spatial- temporal water demand associated with alternative ways of closing demand-supply gap (e.g. water trading, groundwater replenishment, demand management and wastewater reuse), production time and cost, distribution time and cost. The incorporation of one or several of these factors into the proposed MILP model will be a good research direction following this thesis.

- **Integrating planning of water and energy supply**

  Sources of freshwater such as large-scale desalination plants and also sources of renewable energy such as large-scale solar farms are rarely conveniently located next to metropolitan areas due to land constraints. This issue is putting pressure on existing electricity transmission and water transportation infrastructure. To avoid the increase in cost of water and energy associated with long distance electricity transmission and water transportation infrastructure, water and energy utilities have to develop plans for the future considering potential co-benefits in integrated water-energy planning. Thus, another direction for the future work is development of the integrated optimization framework for planning and operation of decentralised urban water and renewable energy supply.

- **Subsurface intake application**

  Given that the defined *beach well scenario* process configuration modelled in Chapter 3, was based upon the site specific assumptions, the configuration we modelled is likely to be feasible at comparable sites around the globe. However, subsurface feedwater at some sites may have less favourable characteristics than that modelled, such as high concentrations of manganese and/or iron, low dissolved oxygen concentration, low temperature, high CO_2 concentration, MTBE contamination and also possibility of salinity change over time. Quantification of the environmental and economic performance of SWRO using subsurface intake under these more challenging conditions deserves further research.

- **LCA database**

  The current study focused only on emissions to air, land and water associated with the supply chain of the SWRO desalination process using the CML2001 characterisation method for LCIA. The method applied herein can assist in the development of mitigation strategies targeting those parts of the SWRO supply chain responsible for the largest environmental impact contributions. However, there are other potential environmental impact categories that may be affected by the employment of beach well or other types of subsurface intakes, for example, marine life (impingement and entrainment) and infrastructure construction impacts (noise impacts associated with drilling wells offshore or onshore). Future models would benefit from the inclusion and quantification of such impact categories in the LCA.

  Finally, the augmented EIO-LCA method (the top-down approach) was used in the current study to account for the impacts of the SWRO construction phase. It is recommended that a detailed and comprehensive process-LCI be developed for the construction phase of desalination plants to help decision makers find possible onsite strategies for reducing these impacts, particularly for subsurface intake construction work such as drilling wells offshore or onshore.

- **Other aspects of decentralization**

  This study simplified some engineering aspects of desalinated water supply system (All assumptions are comprehensively documented and justified in each related chapters). However, future studies could cost and evaluate other engineering aspects of decentralization such as blending the production water with other local sources and integration of decentralized supply system with existing infrastructures. It should be noted such an analysis need other tools such as simulation modeling than the optimization modeling developed herein.

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